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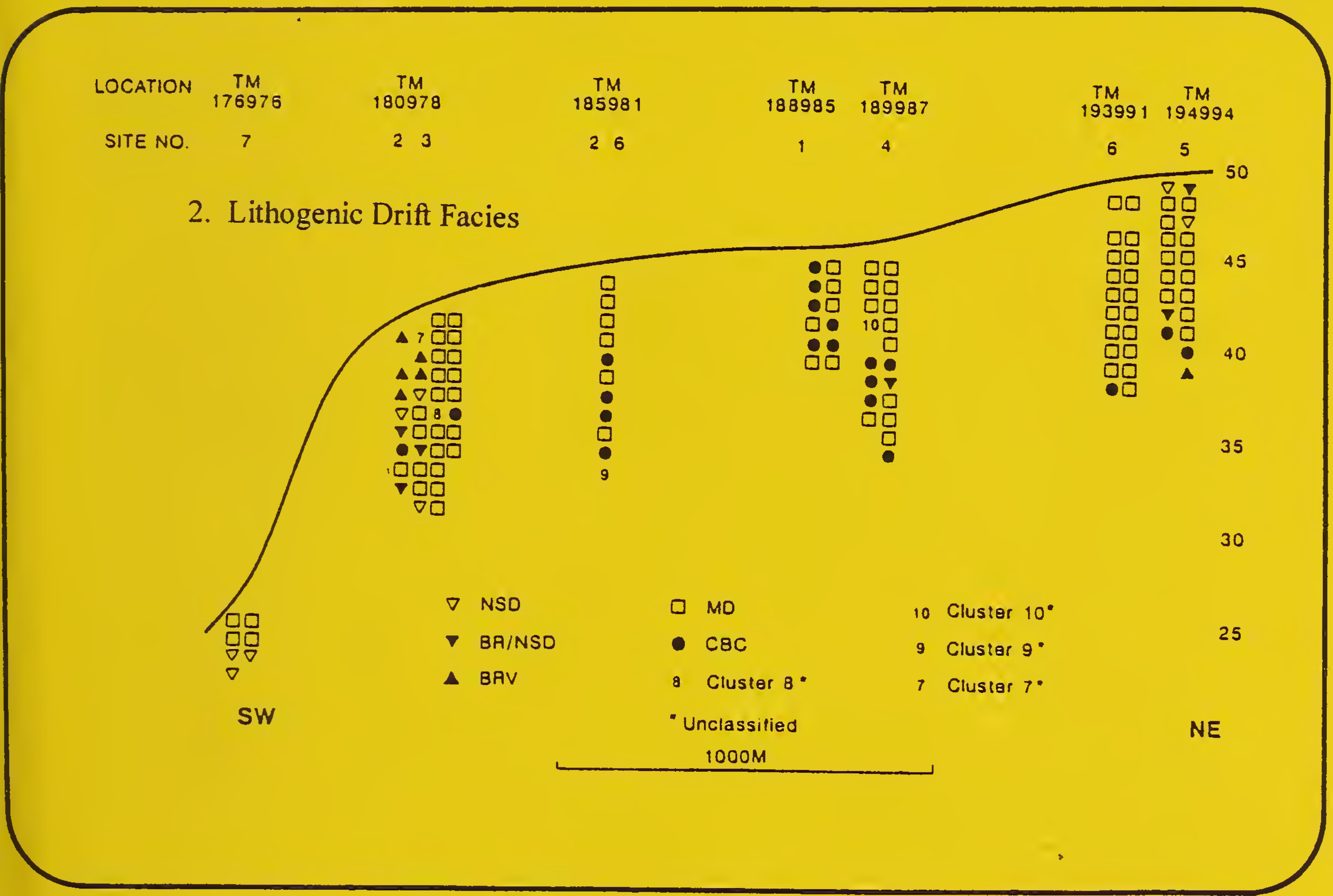
BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

(FOR ARTICLES ON THE GEOLOGY OF EAST ANGLIA)

NO. 51 2001



PUBLISHED 2001

CONTENTS INCLUDE

Lithology, Facies & Stratigraphy
of Anglian Tills

Saline Intrusion of Groundwater

Red Crag Echinoids

BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

No. 51 (2001) Published 2001

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EDITORIAL

Bulletin No. 51 contains two papers by Dr. William Corbett on the recognition, correlation and stratigraphy of glacial till facies from the Chalky Bouldercaly plateau of Norfolk and Suffolk. Dr. Corbett became interested in this topic as part of his work in the Soil Survey, and followed it up in the late 1980s and early 1990s as part of his doctoral research. The publication of this work is timely as it contributes to the current debate on the correlation and stratigraphy of glacial tills in East Anglia provoked by the Geological Survey's remapping programme (see e.g. Hamblin *et al.* 2000, *Quaternary Newsletter*, **92**, 35-43 and Banham *et al.* 2001, *Quaternary Newsletter*, **93**, 5-14). The first paper (p. 5-53 this issue) outlines in some detail the statistical approach used, and the second paper (p. 55-73 this issue) builds on this information. It is intended that a third paper outlining the genesis of these till facies will be published in Bulletin 52.

Bulletin 51 also contains a substantial paper by Mr. Aidan Foley and others on the use of geophysical methods for detecting saline intrusion in coastal groundwater and two shorter papers by Dr. Roger Dixon on the significance of fossil sea urchins from the Red Crag. At the request of some members, brief reports of society field meetings in 2000 are also included (authored by Dr. Dixon). These reports are especially welcome where they contribute new data not easily accessible in other formats (see e.g. p. 122).

As always I welcome the continued submission of papers on all aspects of East Anglian geology, both from regular and new contributors.

Prof. Brian Michael Funnell M.A., Ph.D., F.G.S
(1933-2000)

Bulletin Editor 1983 - 1991

It is with great sadness that I report the death of Prof. Brian Funnell in May 2000, a founder member of the Paramoudra Club, which became the Geological Society of Norfolk in the late 1960s. Brian was a staunch supporter of the activities of the society and this is recorded not least in his support of the Bulletin itself. Indeed Brian edited the Bulletin from 1983 until July 1991, overseeing the production of volumes 33 (1983) to 40 (1990). During his editorship - despite the demands of his academic career in the School of Environmental Sciences at the University of East Anglia - Brian initiated and completed a number of projects to enhance the quality of the Bulletin.

In September 1984 the British Association for the Advancement of Science met at the University of East Anglia in Norwich. Field excursions were part of the geological programme, and Brian persuaded contributors to write overview articles to accompany the field trips. These were published together in Bulletin 34 (1984) now known as the 'East Anglian Geology Issue'. Although a summary of (then) recent work on the Chalk was not included, articles in this volume have nonetheless become much cited and it constitutes an important update to parts of the 1961 collection of papers 'The Geology of Norfolk' (Larwood & Funnell 1961).

In Bulletin 36 (1986) Brian (assisted by others - notably his wife Pat) published an index to Bulletin numbers 1-35. This made location of the earlier material easily accessible for the first time. It is timely that the index is about to be updated and I hope to publish an index for Bulletins 36-51 in the near future.

Finally, Brian and others put a huge amount of effort into ensuring that the earliest Bulletins (1-18) should be generally accessible. In the late 1980s these Bulletins were reset and reprinted in two volumes (38A in 1988 and 39A in 1990). Completion of this project meant that many individuals and libraries were able to complete their run of Bulletins, such that the early discussions and observations are easily available to society members and researchers alike.

In addition to his editorial efforts, Brian was also a regular contributor to the Bulletin. His first contribution was in Bulletin 2 (April 1954), and nineteen further articles followed. Seven of these contributions were co-authored (one of these with his eldest daughter), the last appearing in Bulletin 46 (1996). As might be expected of a prolific researcher, Brian left behind some unfinished work. I hope that some of the important topics he was working on will be published as research notes in future issues of the Bulletin.

More complete obituaries of Brian Funnell have recently been published in the Geological Society of Norfolk 50th Anniversary Jubilee Volume (Vine 2000), and in the Quaternary Research Association Newsletter (West *et al.* 2000). The latter includes a full publication list.

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LARWOOD, G.P. & FUNNELL, B.M. 1961. The Geology of Norfolk. *Transactions of the Norfolk and Norwich Naturalist's Society*, **19**, 270-375.

VINE, F.J. 2000. Professor Brian Michael Funnell, M.A., Ph.D., F.G.S. Tribute given at funeral and service of thanksgiving, 11 May 2000. In: Dixon, R. (ed.), *Geological Society of Norfolk 50th Anniversary Jubilee Volume*, p. 4-6.

WEST, R, VINE, F.J., ANDREWS, J.E., CHAPMAN, M., ATKINSON, T.C. & LORD A. (2000) Obituary: Professor Brian Michael Funnell, M.A., Ph.D., F.G.S. 1933-2000. *Quaternary Newsletter*, **92**, 2-20.

INSTRUCTIONS TO AUTHORS

If possible, contributors should submit manuscripts as word-processor print out accompanied by a disk copy. We can handle most word-processing formats although PC Word, WordPerfect or ASCII files are preferred. In addition we accept typewritten copy and will consider legible handwritten material.

It is important that the style of the paper, in terms of overall format, capitalisation, punctuation, etc. conforms as strictly as possible to that used in Vol. 51 of the Bulletin. Titles and first order headings should be capitalised, centred and in bold print. Second order headings should be centred, bold and lower case. Text should be 1½ line spaced. All measurements should be given in metric units.

References should be arranged alphabetically in the following style.

BALSON, P.S. & CAMERON, T.T.J. 1985. Quaternary mapping offshore East Anglia. *Modern Geology*, **9**, 221-239.

STEERS, J.A. 1960. Physiography and evolution: the physiography and evolution of Scolt Head Island. In: Steers, J.D. (ed.) *Scolt Head Island* (2nd ed.), 12-66, Heffer, Cambridge.

BLACK, R.M. 1988. *The Elements of Palaeontology*. 2nd Ed., Cambridge University Press, Cambridge. 404pp.

Illustrations should be drawn with thin dense black ink lines. Thick lines, close stipple or patches of solid black or grey should be avoided as these can spread in printing. Original illustrations should, before reproduction, be not more than **175mm by 255mm**. Full use should be made of the first (horizontal) dimension which corresponds to the width of print on the page, but the second (vertical) dimension is an upper limit only. Half tone photographic plates are acceptable when their use is warranted by the subject matter, provided the originals exhibit good contrast.

The editors welcome original research papers, notes or comments, and review articles relevant to the geology of **East Anglia** as a whole, and do not restrict consideration to articles covering Norfolk alone. All papers are independently refereed by at least one reviewer.

A STATISTICAL RE-EXAMINATION OF LITHOLOGY AND FACIES VARIATION IN THE CHALKY BOULDERCLAY OF NORFOLK AND SUFFOLK

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ABSTRACT

Cluster Analysis and Principal Component Analysis are used as a statistical approach to classification of Anglian tills from Norfolk and Suffolk. Two forms of till classification were attempted. The first, based on variables that define gross lithology – particle size class and carbonate content - is essentially a traditional approach. The second uses the same data but expresses it as ratios of total carbonate or non-carbonate fractions and magnetic measurements of the fine sand fraction. Cluster Analysis of the former data set identifies distinct facies that can be readily associated with previously recognised tills. It is clear that some units of the North Sea Drift Group are linked with the Breckland Drifts, while other units of the North Sea Drift Group are linked with the Chalky Boulderclay. In contrast, Cluster Analysis of the ratio and magnetic variables results in poor differentiation of till facies.

INTRODUCTION

In many ways the studies of Perrin *et al.* (1973 and 1979) are a focal point of work done on the lithology and facies of the Chalky Boulderclay (Lowestoft Till) in East Anglia. Although these authors recognised the existence of chalkier "Marly Drifts" in north Norfolk, one of their primary findings was that the Chalky Boulderclay represented one lithological unit, albeit with some smooth gradational trends in composition. Earlier work in East Anglia by Baden-Powell (1948) and West and Donner (1956) had identified an upper Wolstonian till (Gipping Till). Baden-Powell and later Evans (1975) also described a site at

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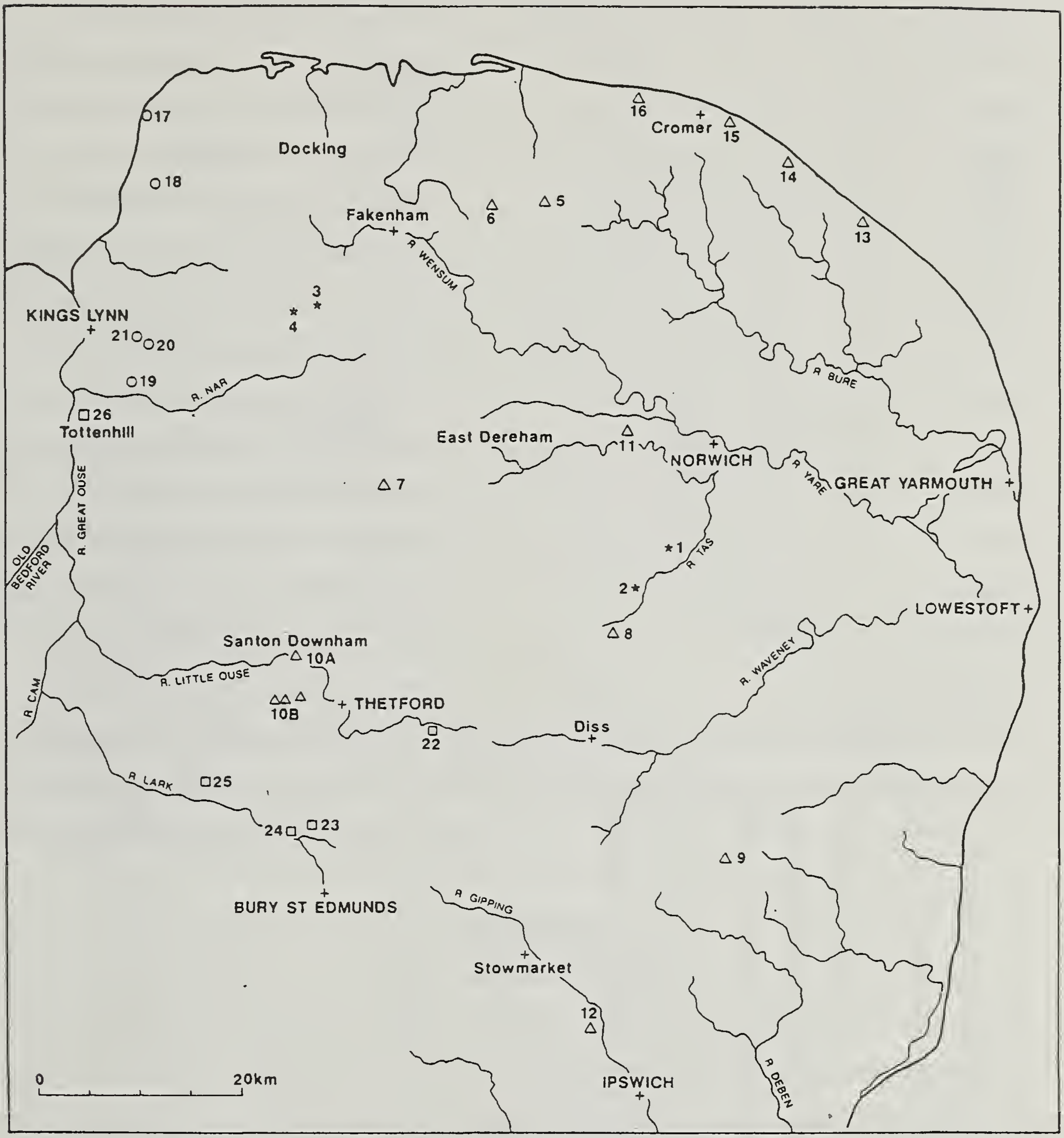
Bawsey in west Norfolk where Marly Drift was found overlying Chalky Boulderclay. To the south of north Norfolk, Ehlers *et al.* (1987 and 1991) recorded sites with Marly Drift; furthermore they noted that while in north Norfolk the Marly Drift consists almost exclusively of chalk material “to the south... especially in the lower parts of the till, major quantities of Jurassic erratics are to be found”... “The younger part of the Marly Drift on the other hand in a glaciodynamic sense represents the ‘Gipping Till’ of Baden-Powell (1948) and West and Donner (1956)”.

The study described here (see also Figure 1 for field and sampling area) originated from work done by the soil surveys in Norfolk and Suffolk between 1967 and 1984. The soil pattern on the Chalky Boulderclay plateau indicated increased permeability on certain sites, most of the plateau having a surface watertable from November to April. Near the plateau perimeter, improved site drainage could be associated with a thinning of the till over the underlying permeable beds (Chalk in the west, pre-glacial sands in the east). However, at other sites, often below secondary interfluves within the plateau, the difference in drainage was associated with a loamier matrix in the underlying till. An example of a such a site is shown in Figure 2, a relief section close to the headwaters of the Wensum (in the south of map sheet TF82 Helhoughton). The figure is based on similar data to that used by Perrin *et al.* (1979; i.e. total carbonate and non-carbonate particle size class) and the site lies to the south of their area of Marly Drift.

The reasons for the differences between the soil surveys findings and those of Perrin *et al.* (1979) can, to some extent be accounted for by the latter’s sampling strategy. Straw (1983) criticised their work on the overall distribution and density of sampling sites. Further criticism can be levelled at; 1) the depth of sampling, which at most sites, was restricted to a drilling depth of 12 feet (3.7 m); 2) the use of mean values when samples were taken from a range of depths at a site, and 3) the use of Trend Surface Analysis as a means of showing geographic variation - thus emphasising smooth variation in till composition. Their drilling sites tended to be flat crests, the aim being to avoid slopes with material derived by movement and mixing with the surface coversand. Second order topographically related discontinuities were thus avoided. Their study emphasised the overall geographic variation of the till surface rather than stratigraphic sequence. There is therefore justification for revisiting the field area of Perrin *et al.* with renewed emphasis on the definition of lithological facies and stratigraphy.



* Transects
△ Individual Cores and Sampling Points
□ 1991 Q.R.A. Excursion Sites
○ Lower Cretaceous Sands

1 Flordon
2 Bunwell
3 Weasenham
4 Rougham
5 Briston
6 Swanton Novers
7 Shipdam
8 Winfarthing
9 Tannington
10A Breckland North
10B Breckland South
11 Hagg's Pit Easton
12 Great Blakenham

13 Happisburgh
14 Mundesley
15 Overstrand
16 West Runton
17 Hunstanton
18 Snettisham
19 Blackborough End
20 Golf Course Pit
21 Bawsey Pit
22 Knettishall
23 Ingham
24 West Stow
25 High Lodge
26 Tottenhill

Fig. 1. Map of the main sampling locations.

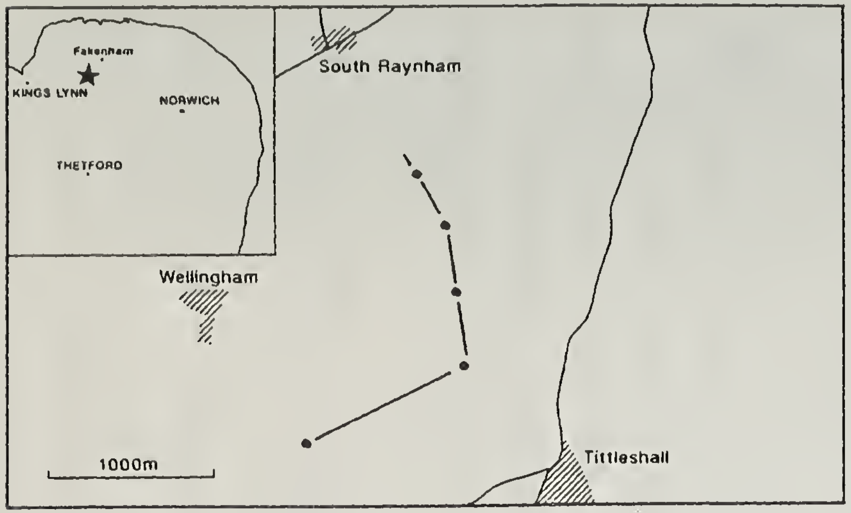


Fig. 2A

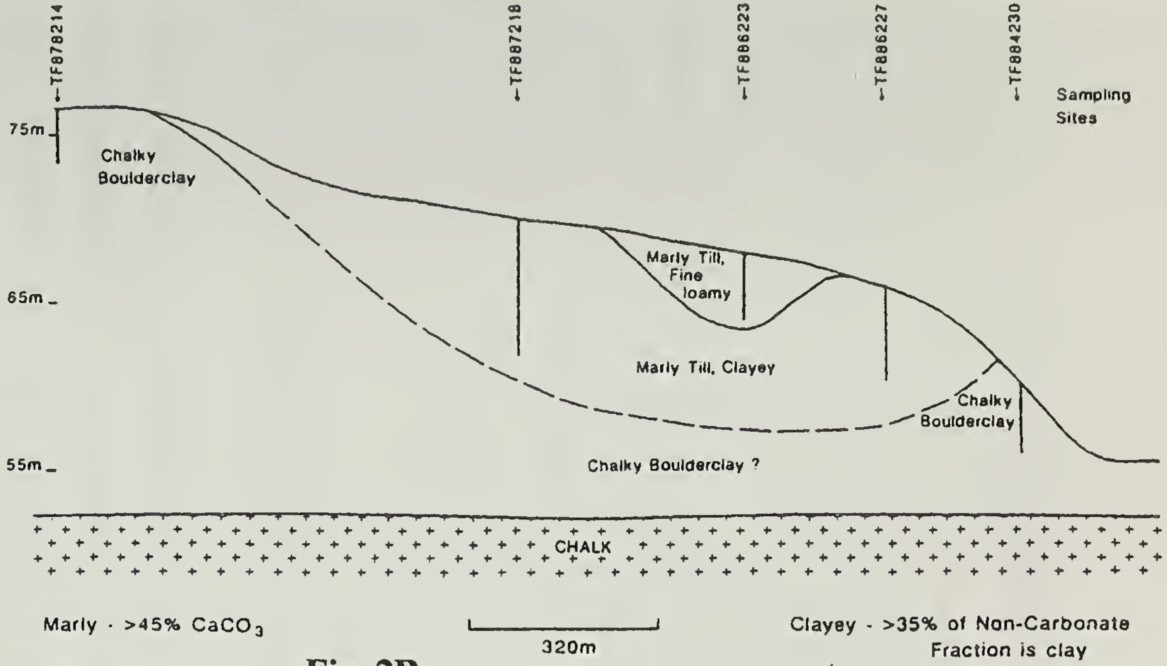


Fig. 2B

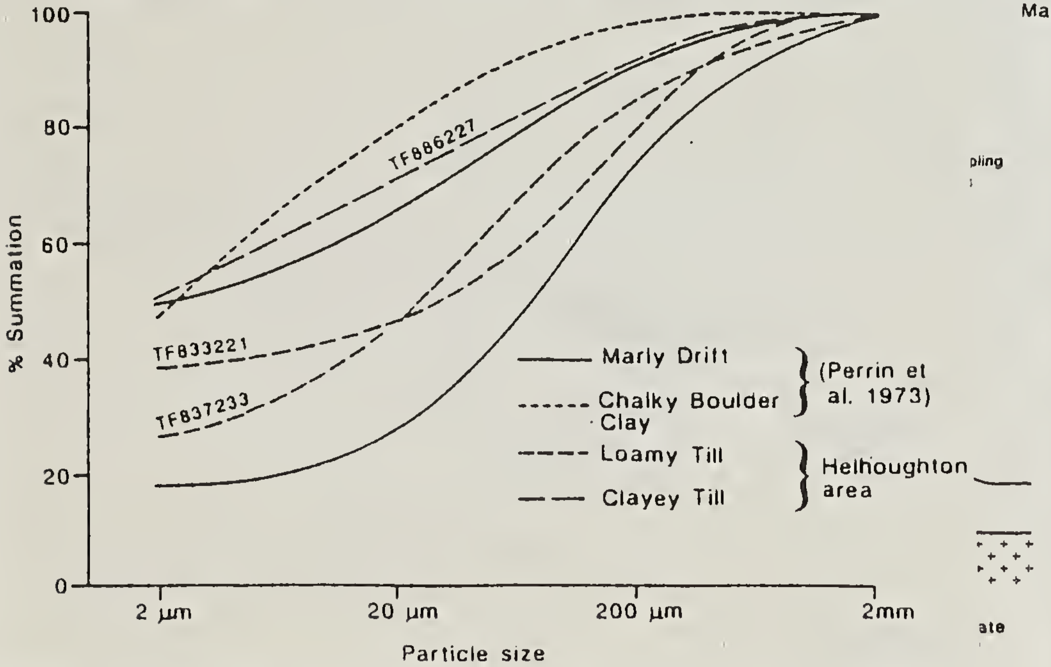


Fig. 2C

Fig. 2A. Location of the Soil Survey of England and Wales transect and sampling sites on 1: 25 000 sheet TF 82SE.

Fig. 2B. Vertical section of the transect in Fig. 2A showing distribution of the Marly Drifts and Chalky Boulderclay in relation to local topography.

Fig. 2C. Particle size class summation curves from specific localites on Fig. 2B (from Corbett 1987).

In this study Cluster Analysis and Principal Component Analysis are used as the statistical approach to till classification. Cluster Analysis in particular anticipates the possible existence of lithologically discrete drift facies defined in the earlier studies. While this study concentrated on recognising and defining vertical variation in the Chalky Boulderclay, the sampling also included material generally accepted as representative of the different Anglian tills (described in detail below). These reference samples were not used as the basis for classification, but simply as comparitors to the units established in this study, and to those recognised by earlier workers. Samples from possible sources of fine sand to the tills were also taken, as Perrin *et al.* (1973) had emphasised the potential importance of the fine sand mineralogy as a provenance indicator.

Two forms of till classification were used in this study. The first, based on variables that define gross lithology is essentially the traditional approach. The second uses the same data but expresses it as ratios of total carbonate or non-carbonate fractions and magnetic measurements of the fine sand fraction. A specific aim was to compare the two classifications and, if possible, to explain and justify differences. The field sampling and data analysis are presented in some detail here, for further use in a companion paper (Corbett 2001) and for future publications. Throughout this paper the term Chalky Boulderclay is broadly synonymous with Lowestoft Till.

METHODS

Field sampling strategy

Most of the samples (457 in total; Fig. 1) were collected by drilling into the Chalky Boulderclay plateau. In the first two field seasons (1990 and 1991), samples were collected at 1m intervals to 13m depth using a "Minute-Man" power auger. In the final field season (1992), with more powerful equipment, key sites were sampled to depths of 23m metres. Reference samples were collected mainly from outcrops and are shown in Figure 1.

The sampling rationale was designed to recognise that, at some localities, vertical variation and possible stratification is present in the Chalky Boulderclay plateau. Also, that, if this variation is widespread, it may be evident in the incised peripheral valleys as a horizontal pattern. In the main study area, the central plateau of Norfolk and northern Suffolk, two site selection strategies were thus used. The first was along transects running locally from high to low ground; two transects were sited in the east of the plateau in the Tas

Valley, at Flordon and at Bunwell, approximately 10 km SW of Norwich. In the west, two more transects were sited at Rougham and at Weasenham, approximately 10 km SW of Fakenham. At Flordon and at Rougham the transects started on the highest ground, very near the eastern and western edges (respectively) of the central plateau (TM194994, TF832213), and ran down into dissecting valleys, the Tas in the east (TM176976) and a headwater tributary of the Wensum (TF834226) in the west (Fig. 1). The Bunwell and Weasenham transects ran down from high ground in the centre of the plateau (TM104934, TF869214), to the valley floors (Fig. 1) of the Tas (TM131197) and Wensum (TF863228).

This strategy attempted to define topographically-related spatial patterns of drift facies and also facilitated local comparison between peripheral and more central plateau sites. Comparison between eastern and western parts of the plateau was also possible. Moreover, a specific aim at Flordon was to establish the lithological and stratigraphic relationships between drift facies on the lower slope of the valley side (equated by Perrin *et al.* (1979) with the Cromer Tills), and the Lowestoft Till identified by the soil survey on the plateau above.

In the relatively undissected central plateau area of central Suffolk to north Norfolk it was assumed that only vertical variation need be taken into account using a single borehole. The central sites were: in north Norfolk, Briston (TG054337) and Swanton Novers (TG014316); in central Norfolk, Shipdham (TF971089); in south Norfolk, Winfarthing (TM114877) and in central Suffolk, Tannington (TM250692).

Three areas were used for reference sampling. 1) At Great Blakenham the Lowestoft Till was sampled at exposures on the plateau at the west end of the main pit (TM100503), and on the slope on its north face (TM108504), where the surface drift is Baden-Powell's Gipping Till (Allen 1984). 2) On the northeast Norfolk coast the North Sea Drift was sampled as follows; the First Cromer Till at Happisburgh (TG383312), 2.5 metres above beach level; the Second Cromer Till at Mundesley, (TG301377), again at 2.5 metres above beach level; the Third Cromer Till at Overstrand, (TG248411), 10 metres below the cliff top; and the contorted drift from West Runton (TG192430). 3) In Breckland the distribution of plateau drift is clearly associated with the Worlington Series Soils which are widespread on large stretches of plateau N and S of the Little Ouse around Santon Downham. In addition the southern plateau includes the site of a mechnically-dug section typical of the horizontal drift pattern on the plateau (Corbett 1973). Sampling sites in the present study were near this at (TL822839) and also to the north of the Little Ouse at (TL828901). Drilled sampling for the mixed drift on, or near, valley side slopes are were at TL806837 and TL810836.

During the Quaternary Research Association's 1991 Field Meeting (Lewis *et al.* 1991), additional till samples were also collected from Knettishall (TL951798); Ingham (TL855715); West Stow (TL798719); High Lodge (TL759734) and Tottenhill (TF636115).

The consistent presence, and mineralogy, of the sand non-carbonate fraction in the Lowestoft Till was pointed out by Perrin *et al.* (1973). They demonstrated a grain size mode of about 150 μm, and showed that the heavy minerals in the 63-105 μm fraction are qualitatively similar for both the Lowestoft Till and the North Sea Drift. They suggested that this sand came from the floor of the North Sea. As mineral magnetic analyses have been used to characterise till units elsewhere (Walden *et al.* 1987; 1992), it was hypothesised that mineralogical differences in the sand fraction might be identified from the remnant magnetism, indicating the nature and origin of the fine sand itself, rather than the till as a whole. To examine this, samples were taken from sandy sediments and rocks that might have acted as source materials.

In west Norfolk, the Lower Cretaceous Carstone was sampled in the north, centre and south of its outcrop: from the Hunstanton cliff face (TG631414), 1.5 metres above beach level; from Snettisham Quarry (TF685384), at depths of 8 and 10 metres below ground surface; and at Blackborough End Quarry (TF673147), at depths of 10 and 15 metres. The Lower Cretaceous Leziate Sands were sampled at the two largest pit exposures: at the Golf Course Pit (TF868183), at depths of 3 and 5 metres; and at Bawsey Pit (TF665194), at depths of 2 and 5 metres. At Shouldham in west Norfolk (TF657085), Tertiary deposits in a pit were sampled at three points approximately 10 metres apart, each 2 metres below the surface.

The Yarmouth Road Beds, as strata flooring part of the North Sea Basin, are a possible source of sand in the North Sea Drift and also, according to Perrin *et al.* (1979), in the Lowestoft Till. Core samples of these beds were provided by the British Geological Survey as shown below, giving a representative sampling spread both N-S and E-W.

Map Sheet	*California*	*(54°N-01°)*	*Core number 53*
Map Sheet	*Silver Well*	*(54°N-02°)*	*Core numbers 169, 141, 138*
Map Sheet	*Flemish Bight*	*(54°N-02°)*	*Core numbers 276, 295, 363, 235, 262, 263.*

From each core, samples were taken from the upper 1 to 2m. These sediments are predominantly fine and medium grained low-carbonate sand, (mean total carbonate content being 7.3%; s.d.5.3).

The Jurassic sandstones of east Yorkshire are possible sources of fine sand in the Lowestoft Till. In this context the Scarborough Formation was sampled from the cliffs at Cloughton (TA020952 and TA020950) and the Staithes and Cleveland Formations were sampled in the cliffs near Staithes (NZ785188 and NZ792187) respectively.

The coversands on the Breckland plateau were similarly sampled as possible sources of admixture to the underlying till. Auger samples from 75 and 125 cm depth were taken near Lynford (TL817918) on the plateau N of the Little Ouse. Samples from a pit at High Lodge, near Brandon (TL817847) were taken at depths of 75 and 150 cm, well below the 40 cm deep base of the zone of iron deposition in podzolization, and the main heavy mineral weathering front (Bateman and Catt, 1985).

Sample analysis

Total carbonate was measured using the Gallenhamp Chittock Apparatus (model cc700; Liss 1970) using 20 ml of 1 molar HCl and an accurately weighed, oven-dried sub-sample of approximately 1 gram. The sub-sample was taken from a 10 gram sample which had been mechanically ground to very fine sand or silt. The grinding not only gave a uniform mix but also ensured that the end point of the reaction was sharp. Replicate analyses on individual samples gave a variation of less than 2% $CaCO_3$ content in fair agreement with Dreimanis (1962) who quoted a maximum deviation of +1.3 and –1.0%.

Particle size separation was achieved by wet sieving an oven-dried, accurately weighed, field sample of approximately 100 grams. The sample was crushed gently and dispersed overnight in a solution of 150 ml of water and 20 ml calgon. Particle size classes measured by wet sieving were: >500 μm, 250-500 μm, 63-250 μm, with the <63 μm fraction being derived by subtraction of the combined weights of the coarser fractions from the original sample weight. These particle size classes differ from those in Perrin *et al.* (1979) who restricted measurements to material <2 mm. Consequently, the sample weights used to calculate percentages refer to ***all*** sizes in this study but only to sand size and below in the work of Perrin *et al.* Another important difference between these studies is that the sieve mesh sizes available for the work reported here, do not quite match those used by Perrin *et* *al.* (1979). This made direct comparison to the results of Perrin *et al.* difficult. The reason for using the 500 μm mesh was to separate off a coarse non-aeolian fraction. This is particularly important for samples taken near the surface, where aeolian sand might have been mixed in by periglacial processes after till deposition.

The oven-dried and weighed material of each size fraction was decalcified to calculate wt% carbonate by weight difference. Decalcification of the two fractions >250 μm was done using 1 molar HCl and of the <250 μm fractions by steam bath treatment with 2 molar sodium acetate buffered to pH 5 with acetic acid. This treatment, a modification of that of Perrin *et al.* (1979), is gentler and does not corrode heavy minerals.

Magnetic measurements were carried out on the non-carbonate fine sand fraction. $CaCO_3$ is a diamagnetic mineral, acquiring in a magnetic field an alignment opposite to that of the field. Its effect on magnetic susceptibility is significant in rocks rich in $CaCO_3$ (Oldfield 1987). For this reason, magnetic measurements were made on the non-carbonate fraction. The fine sand fraction was used because this is the fraction commonly used in mineralogical studies (Perrin *et al.* 1979; Rose *et al.* 1992; Bateman and Rose 1994). For example, Perrin *et al.* (1979) pointed out the persistent occurrence of a non-carbonate sand fraction in the Lowestoft Till, with a strong mode at about 150 μm. Moreover their heavy mineral studies were done on the 63-105 μm fraction. Measurements of mineral magnetic properties were thus carried out on the fine sand fraction (63-250 μm) of all the till samples and also on the samples from possible sources of fine sand (described above), except the Jurassic sandstones that are strongly cemented. Magnetic measurements could be made only on bulk samples of the latter.

Magnetic remanence is a measure of the magnetism retained by the sample after it has been removed from a magnetic field of known strength. The precise measurement used here is the Isothermal Remnanent Magnetism (IRM, see Thompson and Oldfield, 1986). Magnetic remanence was induced in this study by field strengths of 10, 40, 100 and 300 milli-Tessla (mT) in a Mole-Spin Magnetizer and 1000 mT in a Newport Electro-magnet. The retained or remanent magnetism produced by each field strength was measured in a Mole-Spin Magnetometer, the same sample being used for all of the measurements (Maher 1984; Oldfield 1987).

These relative measurements were converted to a standard scale by using the 1000 mT remanence value termed the Saturation Isothermal Remanent Magnetism (SIRM), for each sample as 100% and the remanence values produced in lesser fields as percentages of this. The 1000 mT value was then made absolute by taking into account the weight of sample, standardizing this to a weight of 1 gram. This value provided a measure of the concentration of magnetic mineral grains.

The magnetic properties of the sample were characterised in three ways and of these the absolute 1000 mT value (A1000 mT), was used directly in the data analysis, the others being derived from the magnetic remanence curves. Magnetic remanence curves (Fig. 3), are produced by plotting the various induced field strengths against their equivalent magnetic remanence value as %SIRM. The general shapes of these curves and the differences between them can be used to recognise and differentiate magnetic mineral composition.

Differences were quantified in two ways. The Median Destructive Field (MDF) was derived by determining the field strength necessary to give a 50% remanence value, this being equal to the applied field which would overprint the "softest" 50% of the remanence. (The term "soft" here indicates remanence due to grains whose magnetic domains may be relatively easily re-ordered or overprinted when the sample is exposed to a new magnetic field). The MDF quantifies the magnetic character of the sample for the lower field strengths. The measurement used to characterize the upper field strengths is the difference between the remanence of the 300 mT and 1000 mT values, known as the "Hard" Isothermal Remanent Magnetism (HIRM see also Fig. 3). Both of these derived variables were used in the data analysis.

Data analysis

The carbonate and non-carbonate particle size class measurements were used in the data analysis in two forms termed **Measured Variables** and as their **Derived Ratio Variables**. The first form describes the gross lithology but it has the disadvantage that the values for the individual carbonate and non-carbonate fractions are part of a single percentage scale. Such inter-dependence will usually bias statistical analysis. Derived Ratio Variables, are derived from the Measured Variables. For each sample the value of each carbonate and non-carbonate fraction was divided by the total carbonate and non-carbonate respectively. In this form the inter-dependence of variable values, at least between the carbonate and non-carbonate fractions, is removed and the bias in statistical analysis lessened.

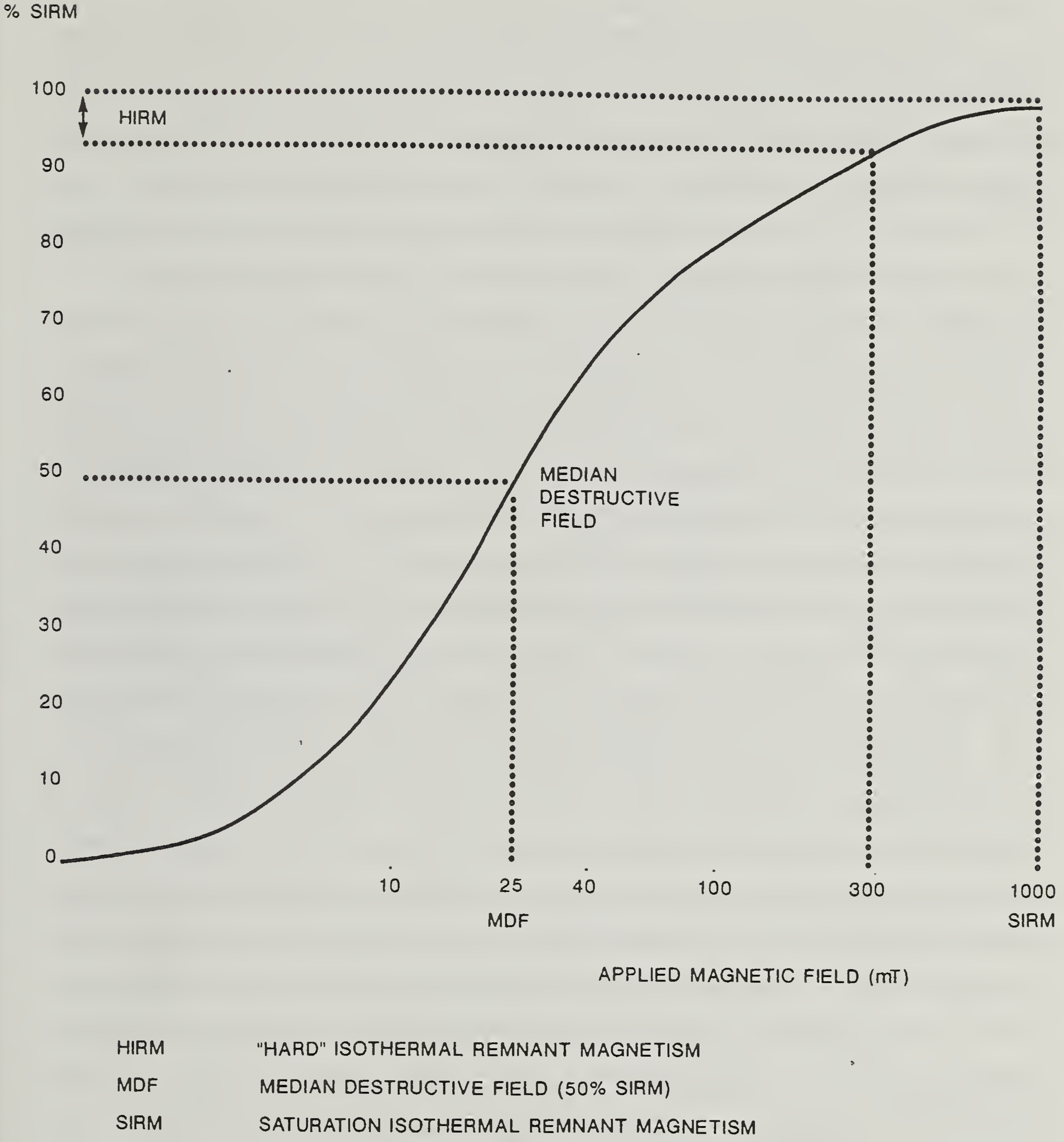


Fig. 3. Schematic example of a magnetic remanence curve.

A further limitation of Measured Variables is that, when carbonate and non-carbonate fractions are on a single percentage scale, differences in the overall carbonate percentage between samples obscure the relative proportions of each within the various particle size fractions. Similarities between till samples in the relative proportions of the individual size class fractions are likely to be associated with a common source area and this in turn may be related to distance travelled, degree of comminution and direction of ice movement. Source rocks may differ in their grain size while carbonate and non-carbonate rocks differ in their erodibility and subsequent comminution. For these reasons, carbonate and non-carbonate fractions were considered separately such that similarities or differences in the grain size distribution between samples, were not then obscured by major variations in the proportions of the individual contributions. The importance of this point is clear when considering the probable source rocks for the Anglian tills, i.e. the Mesozoic sedimentary rocks flooring the western North Sea and east of England. These rocks can be rather clearly divided into almost pure carbonates, with the Chalk predominant, and non-carbonates comprising a variety of Jurassic mudstones and Jurassic, Lower Cretaceous and Pleistocene sands. Thus the Ratio Variable classification of the tills is more likely to reflect the grain size composition of individual sources than the Measured Variables which describe the lithology into which several sources have been mixed by the glacier. It was therefore decided at an early stage in the data reduction to perform the data analysis of Measured Variables and Derived Ratio Variables separately and to compare the results. Furthermore, because the magnetic character of the fine sand fraction may reflect source materials rather than the gross till lithology, it was decided to include magnetic measurements in the Ratio Variable analysis but not in the Measured Variable analysis. Accepting this, the use of Ratio Variables in data analysis should produce a classification more closely allied to the origin of the tills, while taxonomic units derived from Measured Variables should describe variation in gross lithology.

An important element of terminology must be introduced here. As will be described below, the till samples were statistically classified into clusters and groups (or ‘facies’) using the well-established techniques of Cluster Analysis and Principal Components Analysis. Each of these techniques was applied separately to all of the data in its two forms, i.e. its Measured Variables form, and its Derived Ratio Variable form, with magnetic properties included with the latter. The results of the former analysis gave rise to the classification of samples into groups, clusters or "units" which are referred to by two labels, "Measured Variable" units, also known as "Lithological" units. Groups, clusters or "units" derived by analysis of the Ratio Variable plus Magnetic data are termed "Ratio Variable" units, or just "Ratio" units, but also referred to as "Lithogenic" units. The full range of variables available for classification and their definitions are given in Table 1.

In the data analysis only the carbonate and non-carbonate variables (Table 1) were used. The particle size classes were used to derive the listed variables, but were made redundant for analysis because of their use in calculation, i.e. their information is entirely contained within the listed variables. The variables in Table 1 were used in Cluster Analysis and Principal Component Analysis (see below) to recognize and define two forms of taxonomic unit (Fig. 4). The classifications and unit definitions were applied firstly using the Measured Variables to give "lithological" classes and secondly using the Ratio/Magnetism Variables to give "lithogenic" classes. In either case, having distinguished a set of taxonomic units, they can be described in terms of the alternative form of the key variables. For example a cluster of samples, i.e. a taxonomic unit, may have been identified by Cluster Analysis using Measured "Lithologic" Variables. This taxonomic unit can be defined and described in two ways. Firstly, by its set of means and standard deviations, calculated for all samples in the unit, for all of the Measured Variables which were used to isolate and define the cluster or taxonomic unit in the first place. Secondly, these units can also be described by the set of means and standard deviations of the key variables, calculated for all samples in the cluster, but expressed in the Ratio or "Lithogenic" form. This gives a "Lithogenic" interpretation to units identified in terms of their gross lithology.

In a similar way, "Lithogenic" units defined by the results of Cluster Analysis using Ratio Variables can be described in terms of the means and standard deviations of key Measured Variables to give a "Lithological" interpretation. In summary, since clusters or taxonomic units can be defined initially using either Measured or Ratio variables, there are two sets of taxonomic units, each describable by the means and standard deviations of their members using two sets of variables – Measured and Ratio, or defining variable and alternative variable.

Table 1. Variables used for classification and their definitions

Particle Size-Class	**Fractions**	**Abbreviations***	
Carbonate	>500 µm	M CGT500/C>500 or	RCGT500
"	250-500 µm	M C500	R C500
"	63-250 µm	M C250	R C500
"	<63 µm	M C63	R C63
Total Carbonate		TC	
Non-carbonate	>500 µm	M NCGT500/NC>500	R NCGT500/R NC>500
"	250-500 µm	M NC500	R NC500
"	63-250 µm	M NC250	R NC250
"	<63 µm	M NC63	R NC63
Total Non-carbonate		TNC	

*Prefix 'M' refers to the Measured Variable form and 'R' to the Derived Ratio Variable form (see above).

Ratios

NC250/NCGT250 = RFTOC NC250/TNC = RFS CGT500/C63 = CTOF

Magnetic Variables

(a) Field Strengths for Isothermal Remanence Magnetism (IRM) [= primary data]

10 milli Tesslas 10 mT
40 milli Tesslas 40 mT
50 milli Tesslas 50 mT
100 milli Tesslas 100 mT
300 milli Tesslas 300 mT
1000 milli Tesslas 1000 mT (S*IRM)

(b) Derived Magnetic Variables used in statistical analysis

Median Destructive Field (50%)	MDF
Magnetic Difference (1000 mT – 300 mT) [or HIRM]	MAGD
Absolute S*IRM	A 1000 mT

**Saturation*

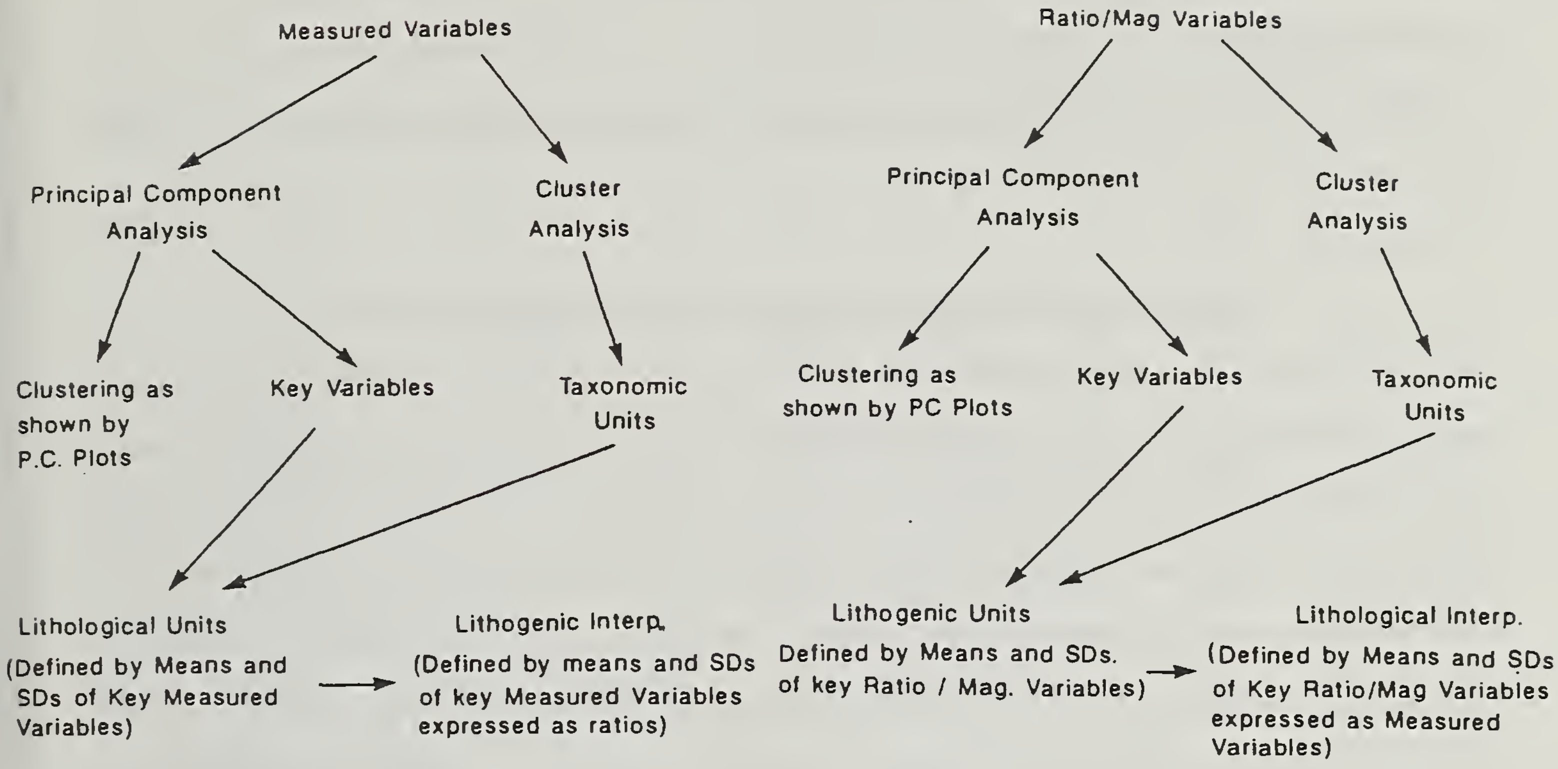

Measured Variables
Principal Component Analysis
Cluster Analysis
Clustering as shown by P.C. Plots
Key Variables
Taxonomic Units
Lithological Units
(Defined by Means and SDs of Key Measured Variables)
Lithogenic Interp.
(Defined by means and SDs of key Measured Variables expressed as ratios)
Ratio/Mag Variables
Principal Component Analysis
Cluster Analysis
Clustering as shown by PC Plots
Key Variables
Taxonomic Units
Lithogenic Units
Defined by Means and SDs. of key Ratio / Mag. Variables)
Lithological Interp.
(Defined by Means and SDs of Key Ratio/Mag Variables expressed as Measured Variables)

Fig. 4. Stages in data analysis.

Cluster Analysis (Appendix 1) was used to recognise and define taxonomic units and **Principal Components Analysis** (Appendix 1), to identify the most important and significant *key variables* in characterising the taxonomic units identified by cluster analysis. In this study the results of Principal Component Analysis were used in two ways. Firstly, the extent to which natural groupings or clusters occur within data sets can usefully be judged visually by plotting individual samples in relation to the axes of any two principal components, provided each principal component explains a high percentage of the variance (Manly 1990). Secondly, having recognised natural groupings by Cluster Analysis these can be defined by the means and standard deviations of certain key variables identified by their principal component weightings.

RESULTS

Results of Cluster Analysis

The raw data are summarised by the means and standard deviations of each variable for each Measured Variable-derived cluster in Table 2 and for each Ratio/Magnetism-derived cluster in Table 3. All suceeding tables describing the lithology and magnetic character of drift facies are derived from Tables 2 and 3.

Cluster Differentiation of Measured (M) Variable Clusters

Table 4 is a re-arrangement of data from Table 2. Here, for each key variable, clusters are ordered according to the value of their individual means. Key or loaded variables are those with the highest loading in the Eigen Factors (see Appendix 1 for definition of these terms). The sequences of means in Table 4 show, within their overall range, the breaks in continuity which define cluster groupings and, within groupings, cluster individuality. The total carbonate (TC) sequence has three cluster groupings. The first of these, with TC means above 40%, includes Clusters M15, M8, M7 and M11 (Table 4). Within this grouping the means and standard deviations for Clusters M7, M8 and M15, all clusters with significant numbers of cases, give clear individual differentiation. The middle cluster grouping for TC contains Clusters M9, M1, M10 and M6 (Table 4), where mean TC percentages are in the low-mid thirties. The means are fairly tightly grouped with marked overlap in standard deviations. The third TC grouping contains Clusters M4, M5, M3, M2 and M13 (Table 4) but also includes Clusters M12 and M14, each with only one case and therefore no standard deviation. TC means in this group are below 20% and although the means are spaced, there is some overlap in standard deviations. The three cluster groupings are themselves sharply differentiated with no standard deviation overlap between adjoining clusters across the group boundaries.

The pattern in the TC sequence is common to all of the key carbonate fractions and also the non-carbonate NC 250 fraction excepting Cluster M6 and the NC 63 sequence (Table 4). The former has typically high mean values in the coarse carbonate fractions and in the NC 250 fraction while in the latter, the cluster sequence differs markedly from that common to the other variables.

The most heavily weighted variable in Eigen Factor I is TC and, in Eigen Factor II NC 63 (see below and Table 8). Table 5 interprets the cluster sequences with respect to each

Table 2. Size class fraction percentages for Measured Variable Derived Clusters (data in microns)

		CARBONATES					NON-CARBONATES				MAGNETISM		
Cluster No.	*n*	*TC*	*C >500*	*C 250-500*	*C 63-250*	*C <63*	*NC >500*	*NC 250-500*	*NC 63-250*	*NC <63*	*MDF*	*HIRM*	*SIRM*
M1	25	35.3	1.5	0.4	1.6	31.7	6.0	9.9	25.7	23.0	59.2	9.0	32.9
		±3.3	±1.1	±0.3	±1.2	±3.3	±3.8	±2.7	±5.9	±5.5	±15.0	±6.6	±18.4
M2	4	3.6	0.1	0.0	0.2	3.4	23.4	42.5	20.8	9.8	52.9	3.3	12.4
		±2.8	±0.1		±0.3	±2.6	±7.9	±8.9	±6.3	±6.9	±9.4	±5.1	±14.0
M3	14	4.6	0.1	0.1	0.1	4.3	6.9	12.6	33.5	42.4	57.7	9.0	34.5
		±4.2	±0.2	±0.1	±0.2	±4.1	±2.7	±3.3	±8.5	±9.1	±10.9	±4.6	±19.6
M4	24	16.7	1.4	0.3	1.1	13.9	3.8	4.6	16.9	58.0	44.1	3.9	81.8
		±6.5	±1.0	±0.2	±0.6	±5.3	±1.4	±1.5	±4.4	±6.7	±9.3	±4.5	±50.6
M5	9	11.8	2.2	0.3	1.6	7.8	19.0	31.5	33.2	4.5	51.3	0.2	88.1
		±4.8	±1.8	±0.2	±1.5	±3.7	±5.0	±4.6	±5.4	±3.4	±3.9	±5.5	±61.5
M6	6	30.3	4.7	0.7	3.1	21.9	7.5	18.9	38.3	5.1	68.5	18.5	51.0
		±6.8	±3.7	±0.5	±1.5	±5.9	±3.2	±2.2	±4.5	±4.2	±9.4	±6.4	±20.5
M7	103	47.4	4.9	0.9	2.3	39.3	2.9	3.7	8.7	37.3	48.9	9.7	53.0
		±4.4	±1.8	±0.3	±0.5	±3.8	±2.0	±2.1	±3.2	±6.8	±12.3	±8.2	±24.8
M8	254	63.5	6.1	1.1	3.1	53.2	3.2	4.5	8.8	20.1	43.6	6.9	54.3
		±6.4	±2.3	±0.3	±0.6	±6.1	±1.4	±1.7	±2.4	±4.9	±11.2	±7.6	±31.6
M9	2	35.6	6.1	0.7	1.7	27.2	34.2	8.3	11.3	10.7	33.2	-0.2	134.4
		±1.2	±1.9	±0.1	±0.1	±0.7	±4.9	±3.5	±2.9	±0.3	±4.8	±5.4	±53.2
M10	11	34.1	2.7	0.6	1.5	29.3	2.7	3.6	12.1	47.5	45.6	4.7	63.2
		±3.8	±0.9	±0.2	±0.4	±3.2	±1.3	±1.2	±6.3	±4.4	±8.6	±5.8	±26.5
M11	2	42.3	15.1	1.0	2.8	23.5	6.0	7.6	12.9	31.3	38.0	4.5	61.7
		±4.8	±1.8	±0.1	±1.1	±2.1	±0.1	±0.8	±0.7	±4.6	±2.3	±3.6	±23.0
M12	1	0.0	0.0	0.0	0.0	0.0	5.5	31.1	32.6	30.9	66.7	20.2	20.0
M13	2	1.8	0.0	0.0	0.0	1.8	0.4	3.1	81.4	13.4	61.5	3.6	6.0
		±2.6				±2.5	±0.5	±4.0	±4.0	±2.0	±1.2	±0.7	±0.5
M14	1	2.7	0.0	0.0	0.0	2.7	5.9	11.2	61.0	19.2	56.9	-5.0	6.3
		±0.0											
M15	11	84.1	1.3	0.6	1.7	80.4	1.9	2.3	4.1	7.5	28.7	5.0	66.6
		±5.1	±1.1	±0.3	±0.2	±5.1	±0.7	±1.0	±1.6	±3.0	±6.0	±10.5	±23.0

n = number of cases, TC = Total Carbonate, MDF = Median Destructive Field HIRM = 'Hard' Isothermal Remanent Magnetism, SIRM = Saturation Isothermal Remanent Magnetism. Other abbreviations as Table 1.

Table 3. Size class fraction percentages for Ratio Variable Derived Clusters (data in microns)

		CARBONATES					NON-CARBONATES				MAGNETISM		
Cluster No.	*n*	*TC*	*C >500*	*C 250-500*	*C 63-250*	*C <63*	*NC >500*	*NC 250-500*	*NC 63-250*	*NC <63*	*MDF*	*HIRM*	*SIRM*
R1	257	58.2 ±10.5	5.6 ±2.4	1.0 ±0.3	2.8 ±0.7	48.8 ±9.1	3.0 ±1.6	4.6 ±2.3	9.5 ±4.8	24.7 ±9.4	46.0 ±8.9	8.1 ±7.0	38.4 ±10.9
R2	21	5.2 ±4.0	0.1 ±0.2	0.1 ±0.1	0.3 ±0.6	4.7 ±3.6	11.4 ±9.7	19.2 ±14.6	31.7 ±12.5	32.4 ±23.2	57.5 ±10.9	6.1 ±6.7	22.5 ±15.2
R3	28	17.4 ±7.7	1.7 ±1.3	0.3 ±0.2	1.1 ±0.6	14.3 ±6.5	7.7 ±6.4	10.8 ±10.2	21.2 ±8.2	42.9 ±20.8	44.3 ±6.5	4.4 ±4.6	82.8 ±15.5
R4	1	14.3	4.9	0.4	3.3	5.7	18.0	33.2	28.2	6.3	50.3	-3.1	210.9
R5	16	35.8 ±5.5	3.3 ±2.8	0.6 ±0.4	2.3 ±1.6	29.6 ±6.9	4.1 ±2.3	10.5 ±5.7	27.3 ±11.6	22.4 ±15.1	74.6 ±9.5	18.3 ±8.6	30.7 ±9.3
R6	102	57.4 ±14.9	5.2 ±2.9	1.0 ±0.4	2.5 ±0.8	48.7 ±14.6	3.7 ±2.6	4.3 ±2.6	9.2 ±4.3	25.3 ±12.3	41.7 ±10.8	5.9 ±7.4	72.5 ±12.1
R7	2	11.7 ±5.4	1.2 ±0.8	0.3 ±0.1	2.7 ±2.9	7.7 ±1.6	10.6 ±10.5	18.1 ±18.0	20.6 ±5.7	39.1 ±39.6	49.2 ±3.7	-4.4 0.0	161.4 ±14.1

R8	1	71.3	3.5	0.8	3.9	63.1	2.0	3.5	6.1	17.1	132.9	43.4	43.2
R9	3	47.1 ±10.1	5.3 ±1.8	0.8 ±0.3	2.4 ±0.6	38.6 ±10.9	14.7 ±20.0	4.9 ±0.9	10.0 ±2.9	23.3 ±10.8	30.9 ±1.8	1.3 ±5.0	161.5 ±10.8
R10	3	40.7 ±6.2	4.8 ±3.8	0.5 ±0.2	1.5 ±0.5	33.9 ±4.1	3.1 ±1.5	3.3 ±1.8	13.2 ±11.2	39.6 ±8.3	86.9 ±3.5	22.7 ±15.4	88.8 ±4.2
R11	1	24.8	3.8	0.6	1.5	18.9	4.6	4.2	14.4	52.0	36.6	1.6	257.4
R12	21	61.7 ±9.0	5.6 ±2.0	1.2 ±0.4	3.1 ±0.7	51.7 ±8.6	4.1 ±2.4	4.3 ±1.8	9.5 ±3.1	20.3 ±6.7	34.6 ±6.4	2.4 ±3.2	115.1 ±12.8
R13	1	69.4	4.9	1.1	3.4	60.0	2.4	4.2	8.0	16.0	26.2	-4.2	239.7
R14	1	3.6	0.0	0.0	0.0	3.6	0.0	0.2	84.2	12.0	60.7	4.1	5.6
R15	1	64.9	0.5	0.3	1.3	62.8	2.8	5.4	8.4	18.5	17.8	5.0	276.2

n = number of cases, TC = Total Carbonate, MDF = Median Destructive Field HIRM = 'Hard' Isothermal Remanent Magnetism, SIRM = Saturation Isothermal Remanent Magnetism. Other abbreviations as Table 1.

Table 4. Measured Variable Derived Clusters ordered by the mean values of their loaded variables

TC	C63	NC250	NC63
M15 MDv 84.1 ±5.1	M15 MDv 80.4 ±5.1	M15 MDv 4.1 ±.6	M5 NSD/GF 4.5 ±.4
M8 MD 63.5 ±6.4	M8 MD 53.2 ±6.1	M7 CBC 8.7 ±3.2	M6 BR 5.1 ±4.2
M7 CBC 47.4 ±4.4	M7 CBC 39.3 ±3.8	M8 MD 8.8 ±2.4	M15 MDv 7.5 ±3.0
M11 MDv2 42.3 ±4.8	M1 NSD2 31.7 ±3.3	M9 BRv 11.3 ±2.9	M2 GF 9.8 ±6.9
M9 BRv 35.6 ±1.2	M10 CBC/ NSD 29.3 ±3.2	M10 CBC/ NSD 12.1 ±6.3	M9 BRv 10.7 ±0.3
M1 NSD2 35.3 ±3.3	M9 BRv 27.2 ±0.7	M11 MDv2 12.9 ±0.7	M13 NSDv 13.4 ±2.0
M10 CBC/ NSD 34.1 ±3.8	M11 MDv2 23.5 ±2.1	M4 NSD3 16.9 ±4.4	M14 NSDv 19.2 ±0.0
M6 BR 30.3 ±6.8	M6 BR 21.9 ±5.9	M2 GF 20.8 ±6.3	M8 MD 20.1 ±4.9
M4 NSD3 16.7 ±6.5	M4 NSD3 13.9 ±5.3	M1 NSD2 25.7 ±5.9	M1 NSD2 23.0 ±5.5
M5 NSD/GF 11.8 ±4.8	M5 NSD/GF 7.8 ±3.7	M12 NSDv 32.6 ±0.0	M12 NSDv 30.9 ±0.0
M3 NSD1 4.6 ±4.2	M3 NSD1 4.3 ±4.1	M5NSD/GF 33.2 ±5.4	M11 MDv2 31.3 ±4.6
M2 GF 3.6 ±2.8	M2 GF 3.4 ±2.6	M3 NSD1 33.5 ±8.4	M7 CBC 37.3 ±6.8
M14 NSDv 2.7 ±0.0	M14 NSDv 2.7 ±0.0	M6 BR 38.3 ±4.5	M3 NSD1 42.4 ±9.1
M13 NSDv 1.8 ±2.5	M13 NSDv 1.8 ±2.5	M14 NSDv 61.0 ±0.0	M10 CBC/ NSD 47.5 ±4.4
M12 NSDv 0.0 ±0.0	M12 NSDv 0.0 ±0.0	M13 NSDv 81.4 ±4.0	M4 NSD3 58.0 ±6.7

Column headers are defined in Table 1. Bold lines indicate breaks in cluster grouping continuity.

CBC =Chalky Boulder Clay; MD = Marly Drift; BR = Breckland Drift; NSD =North Sea Drift; GF = Glacio fluvial v = variant.

Table footnote: To facilitate comparison between different variable sequences, the ordering of means, low to high or high to low is where necessary reversed. This arrangement identifies cluster sequences common to different variables, common subdivisions within these, and inconsistencies in both or either. The arrangement also provides an opportunity to assess, using the standard deviations, the significance of the difference in means between adjoining clusters.

of these two variables to assess the degree of differentiation of adjoining clusters. The table consists of three sections, the upper one dealing with the TC sequence and the middle one, the NC 63 sequence. The third section compares the results of the top two. The top two sections first list across the page the cluster numbers whose mean values are so separated in Table 4 that there is no overlap in their standard deviations. This is judged to be clear differentiation and it is applied systematically in Table 4 by starting at the bottom cluster in the TC and NC 63 sequences and working up the sequence column to the cluster where differentiation occurs. This cluster pair is noted and the process is repeated up the sequence, cluster by cluster, the differentiated pairs in Table 5 being listed across the page. The lists consist of only the nearest differentiated pairs. In effect these differentiated pairs mark the limits, within the sequence, of the enclosed undifferentiated pairs. The second row in each of the top two sections in Table 5 lists the enclosed undifferentiated clusters.

The third section at the bottom of Table 5 brings together in two adjacent rows, ordered lists of the undifferentiated clusters for the two most heavily loaded variables. Only those undifferentiated clusters common to both the TC and NC 63 lists remain wholly undifferentiated, the corollary being that all other pairs are differentiated by at least one of the variables. The completely undifferentiated cluster pairings common to both variable lists are in bold type. They are 1/11 and 7/11.

Thus, using just two key variables, Cluster Analysis of Measured Variables clearly differentiates all but two pairs of clusters. Both pairs include Cluster 11 which has only two cases. This is only a minor taxonomic limitation and the classification is judged to have produced, for the most part, clearly differentiated and useful lithological units at the single-cluster level.

Cluster Differentiation of Ratio/Magnetism R Variable Clusters

Sequences of Measured Variable means (Table 6) are derived by converting ratios (from Table 3) into percentages. As in Table 4, breaks in the sequences of means give three groupings of clusters and again in these groupings there is some common continuity between the different variable sequences. Here, however, it is particularly noticeable that within cluster groupings, cluster means are close and their standard deviations have broad overlaps. Similarly, the data in Table 7 are derived from Table 6 and differ only in that here, for

Table 5. Measured Variable Cluster differentiation using total carbonate (TC) and non-carbonate (NC 63) means and standard deviations

TC

Differentiated Clusters	2/5	3/4	5/6	4/6	6/11	10/7	1/7	9/11	11/8	7/8	8/15
Undifferentiated Clusters	13/2	2/3	3/5	5/4	6/10	6/1	6/9	10/1	10/9	10/11	1/9
	1/11	11/7									

NC 63

Differentiated Clusters	4/3	10/11	3/1	7/1	11/8	1/9	8/9	9/6			
Undifferentiated Clusters	4/10	10/3	10/7	3/7	3/11	7/11	11/1	1/8	9/2	9/15	2/15
	2/6	2/5	6/5	15/5	15/6						

Ordered list of Undifferentiated Clusters

TC	1/6	1/9	1/10	**1/11**	2/3	3/5	4/5	6/9	6/10	**7/11**	9/10	10/11
NC 63	1/8	**1/11**	2/5	2/6	2/9	2/15	3/7	3/10	3/11	4/10	5/6	5/15
	6/15	9/15	**7/11**	7/10								

(**Bold values** are undifferentiated by both TC and NC 63)

cluster differentiation, three heavily loaded variables are used. For Eigen Factor I these are CGT250R and C63R and for Eigen Factor II, NC63R (see Table 9).

The classification produced by Cluster Analysis using Ratio Variables is markedly different to that produced from Measured Variables. Of the three most heavily loaded variables, Cluster R1 with 257 cases cannot be distinguished from Cluster R6 (102 cases), or from Cluster R12 (21 cases). Furthermore Cluster R6 cannot be differentiated from Cluster R5 (16 cases), or from Cluster R12. There is thus a lack of differentiation between the clusters with the largest numbers of cases. This implies that classification based on Ratio/Magnetism Variables does not produce units that are different in gross lithology terms.

Table 6. Ratio/Magnetism Derived Clusters ordered by measured variable means of their loaded variables

C>250R	C63R	NC63R	NC>250R	MDF
R12 MDv 6.9 ±2.3	R8 63.1 ±0.0	R 4 6.3 ±0.0	R 14 0.2 ±0.0	R 15 17.8 ±0.0
R1 MD 6.6 ±2.6	R15 62.8 ±0.0	R14 12.0 ±0.0	R8 5.5 ±0.0	R13 26.2 ±0.0
R6 CBC 6.2 ±3.1	R13 60.0 ±0.0	R13 16.0 ±0.0	R10 CBCv 6.5 ±3.3	R9 30.9 ±1.8
R9 6.2 ±1.6	R MDv 51.7 ±8.6	R8 17.1 ±0.0	R13 6.6 ±0.0	R12 MDv34.6 ±6.4
R13 6.0 ±0.0	R1 MD 48.8 ±9.1	R15 18.5 ±0.0	R1 MD 7.6 ±3.5	R11 36.6 ±0.0
R4 5.3 ±0.0	R6 CBC 48.7 ±14.6	R12 MDv20.3 ±6.7	R6 CBC 8.0 ±4.7	R6 CBC 41.7 ±10.8
R10 CBCv 5.3 ±4.0	R9 38.6 ±10.9	R5 BR/ NSD 22.4 ±15.1	R15 8.2 ±0.0	R3 BRv 44.3 ±6.5
R11 4.4 0.0	R10 CBCv33.9 ±4.1	R9 23.3 ±10.8	R12 MDv 8.5 ±3.7	R1 MD 46.0 ±8.9
R8 4.3 0.0	R5 BR/ NSD 29.6 ±6.9	R1 MD 24.7 ±9.4	R11 8.8 ±0.0	R7 49.2 ±3.7
R5 BR/ NSD 3.9 ±3.1	R11 18.9 ±0.0	R6 CBC 25.3 ±12.3	R5 BR/ NSD 14.6 ±7.5	R4 50.3 ±0.0
R3 BRv 2.1 ±1.4	R3 BRv 14.3 ±6.5	R2 NSD 32.4 ±23.2	R3 BRv 18.5 ±15.2	R2 NSD 57.5 ±10.9
R7 1.4 ±0.8	R7 7.7 ±1.6	R7 39.1 ±39.6	R9 19.5 ±20.8	R14 60.7 ±0.0
R15 0.8 ±0.0	R4 5.7 ±0.0	R10 CBCv39.6 ±8.3	R7 28.6 ±28.6	R5 BR/ NSD 74.6 ±9.5
R2 NSD 0.2 ±0.3	R2 NSD 4.7 ±3.6	R3 BRv 42.9 ±20.8	R2 NSD 30.7 ±22.8	R10 CBCv86.9 ±3.5
R14 0.0 ±0.0	R14 3.6 ±0.0	R11 52.0 ±0.0	R4 51.2 ±0.0	R8 132.9 ±0.0

Clusters R4, R7, R8, R9, R11, R13, R14 and R15 are unclassed.

Column headers are defined in Table 1. Bold lines indicate breaks in cluster grouping continuity.

CBC =Chalky Boulder Clay; MD = Marly Drift; BR = Breckland Drift; NSD =North Sea Drift; v = variant.

Table 7. Ratio/Magnetism Cluster differentiation using carbonate C250R, carbonate C63R and non-carbonate NC63R means and standard deviations

C>250

Differentiated Clusters	2/7	7/9	3/9									
Undifferentiated Clusters	7/3	7/5	7/10	3/5	3/10	5/10	5/9	5/6	5/1	5/12	10/9	10/6
	10/1	10/12	9/6	9/1	9/12	6/1	6/12	1/12				

C63

Differentiated Clusters	2/5	7/5	3/5	5/1	10/1							
Undifferentiated Clusters	2/7	2/3	7/3	5/10	5/9	5/6	10/9	10/6	9/6	9/1	9/12	6/1
	6/12	1/12										

NC63

Differentiated Clusters	10/12											
Undifferentiated Clusters	3/10	3/7	3/2	3/6	3/1	3/9	3/5	3/12	10/7	10/2	10/6	10/1
	0/9	10/5	7/2	7/6	7/1	7/9	7/5	7/12	2/6	2/1	2/9	2/5
	2/12	6/1	6/9	6/5	6/12	1/9	1/5	1/12	9/5	9/12	5/12	

Ordered list of Undifferentiated Clusters

C>250	1/5	**1/6**	**1/9**	1/10	**1/12**	3/5	**3/7**	3/10	**5/6**	5/7	**5/9**	**5/10**
	5/12	**6/9**	**6/10**	**6/12**	7/10	**9/10**	**9/12**	10/12				
C63	**1/6**	**1/9**	**1/12**	2/3	2/7	**3/7**	**5/6**	**5/9**	**5/10**	6/9	**6/10**	**6/12**
	9/10	**9/12**										
NC63	1/2	1/3	1/5	**1/6**	1/7	**1/9**	1/10	**1/12**	2/3	2/5	2/6	2/7
	2/9	2/10	2/12	3/5	3/6	**3/7**	3/9	3/10	3/12	**5/6**	5/7	**5/9**
	5/10	5/12	6/7	**6/9**	**6/10**	**6/12**	7/9	7/10	7/12	**9/10**	**9/12**	10/12

(**Bold values** are undifferentiated by C >250, C63 and NC63)

Principal Component Analysis

The results of Principal Component Analysis of Measured Variables are summarised in Table 8. The first Eigen Factor (or Principal Component) explains 58% of the total variance and its most heavily loaded variables are TC and C63. All carbonate variables show high positive loading while non-carbonate variables show moderate to large negative loading. This Eigen Factor is thus essentially a "Carbonate-Non Carbonate" axis.

The second and third Eigen Factors together explain a further 30% of the variance and their most heavily loaded variables are NC63 and CGT500 respectively. Essentially, both these factors describe coarse-to-fine variation in grain size distribution, Eigen Factor II being most heavily loaded by non-carbonates, Eigen Factor III by carbonate variables. Thus, the three factors combined describe the overall carbonate content of the sample (Factor I), with high scores on Factor II indicating a predominance of coarse non-carbonate material, and high scores on Factor III indicating predominance of coarse carbonate (see figure insert in Table 8).

The results of Principal Component Analysis of Ratio/Magnetism Variables are summarised in Table 9. The first two Eigen Factors make almost equal contributions to account for 54% of the total variance. Their most heavily loaded variables are CGT250R, C63R, CGT500R, NC63R and NCGT250R, carbonate loaded variables being in Factor I and non-carbonate loaded variables in Factor II. The 63R fractions for both factors have a negative loading, the other fractions a positive one.

Thus Eigen Factor I mainly represents grain size of the carbonate particles, with a predominance of coarse grained carbonates giving a high factor score whereas fine grained carbonates produce a large negative score. Eigen Factor II indicates the grain size distribution of the non-carbonate in a similar way. Factors III and IV relate to magnetic variables and grain size distribution in a complex way. Factor III has large positive loading on two of the magnetic variables, MDF and MAGDIFF. Samples with relatively hard remanent magnetisation would have high scores on this factor. Conversely, samples with a large saturation remanence (A1000mT) value, indicating a high concentration of strongly magnetic mineral grains, have a tendency to negative loading on this factor, as do samples with a high incidence of coarse grains in the non-carbonates. These last two variables are most likely related to the concentration of detrital magnetite in coarse grains ultimately derived from igneous rocks. As magnetite gives rise to relatively soft magnetisation

Table 8. Eigen factor variances and matrix for Measured Variables

Variable	Factor 1	Factor 2	Factor 3
TNC	-.940	-.139	.300
TC	**.940**	.139	-.300
CGT500	.727	.294	.577
CGT250	.762	.289	.555
C500	.831	.196	.296
C250	.809	.281	.060
C63	**.882**	.088	-.451
NCGT500	-.569	.662	.057
NC500	-.689	.640	-.007
NC250	**-.765**	.149	.008
NC63	-.311	**-.807**	.411
NCGT250	-.690	.700	.021

Factor	Eigen Value	% of variance	Cumulative %
1	6.96220	58.0	58.0
2	2.34441	19.5	77.6
3	1.28834	10.7	88.3

(Variable abbreviations are defined in Table 1)

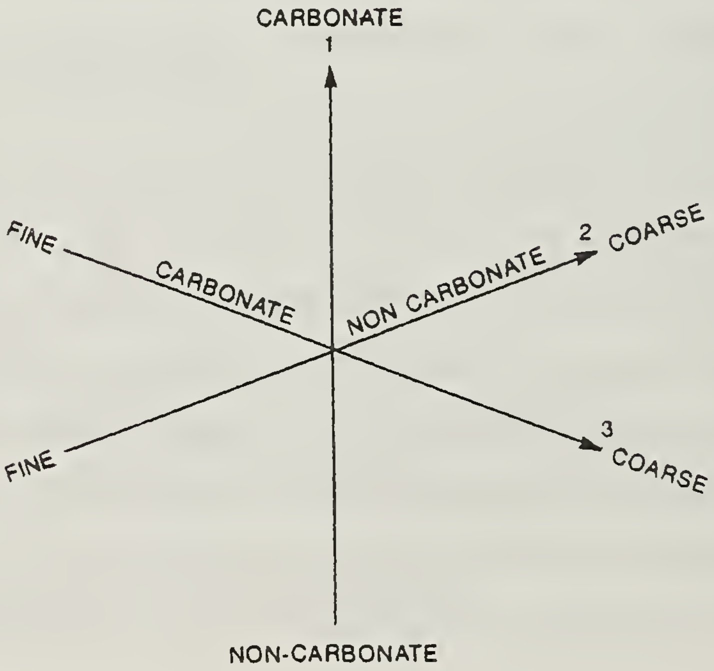
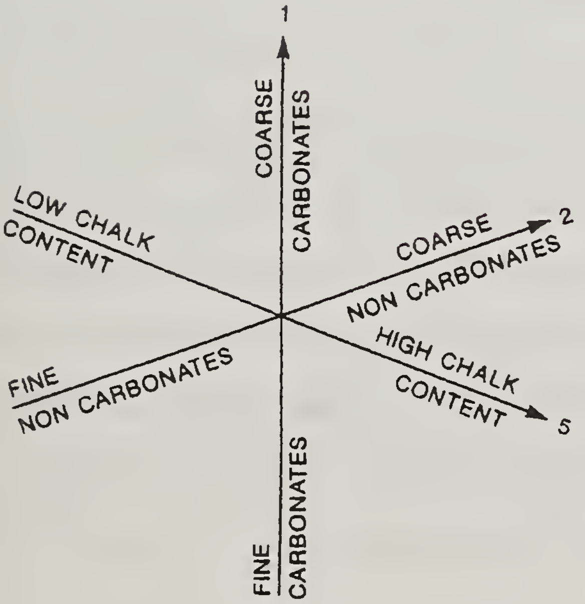


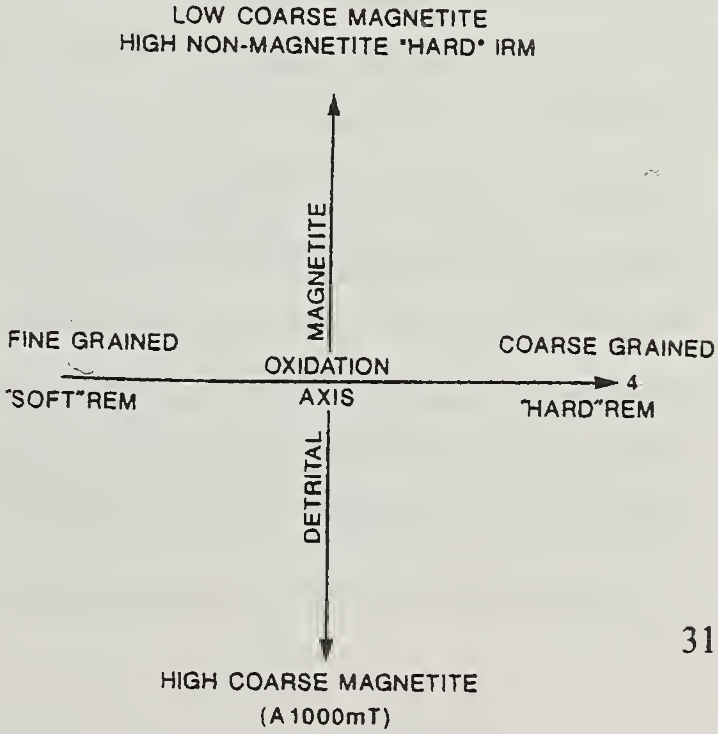
Table 9. Eigen factor variances and matrix for Ratio/Magnetism Variables

Variable	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
TC	.126	-.238	-.333	.222	.720
MDF	-.129	.115	**.837**	.326	-.133
MAGDIFF	.097	-.108	.700	.501	.090
A1000mT	.216	.142	-.528	-.199	-.258
CGT500R	.892	.310	.105	-.034	.229
CGT250R	**.916**	.302	.093	-.054	.179
C500R	.671	.127	-.016	-.157	-.209
C250R	.504	.380	.067	-.035	-.436
C63R	**-.911**	-.374	-.099	.056	.008
CTOFINE	.835	.419	.132	-.065	.161
NCGT500R	-.106	.657	-.401	.353	.070
NCG250R	-.210	**.861**	-.269	.327	.001
NC500R	-.249	.831	-.092	.228	-.058
NC250R	-.493	.672	.277	-.355	.123
NC63R	.402	**-.910**	.017	-.012	-.068
RFS	-.494	.673	.277	-.355	.123
RFTOC	-.211	.044	.289	-.637	.251

Factor	Eigen Value	% of Variance	Cumulative %
1	4.76811	28.0	28.0
2	4.36658	25.7	53.7
3	2.10967	12.4	66.1
4	1.42671	8.4	74.5
5	1.06180	6.2	80.8

(Variable abbreviations are defined in Table 1)





compared with antiferimagnetic minerals such as haematite, the positive loading of MDF and MAGDIFF on Factor III may reflect relatively high proportions of haematite. Thus high positive scores on Factor III probably indicate weak remanence with a lower absolute concentration of magnetite and a higher relative proportion of haematite. Negative scores indicate higher concentrations of relatively coarse-grained magnetite. Factor IV shows moderate positive loading of MAGDIFF, the hard component of IRM and moderate negative loading of the ratio RFTOC which reflects the relative ratio of fine to coarse sediments among the non-carbonates. Thus, high scores on this factor indicate a predominance of coarse-grained material with the presence of "hard" IRM minerals, possibly not magnetite.

Factor V primarily reflects the overall carbonate content of the till (TC), with a negative loading on medium sand sized carbonates, perhaps because the principal source of carbonate is chalk, which gives rise to pebble and coarse sand when broken and silt/clay sized material when ground. Thus, a high chalk content will be reflected in a low Ratio percentage of medium sand carbonate.

In Figure 5A clusters derived from Measured Variables are plotted for Eigen Factors I and II. Almost all clusters in Figure 5A have some distinct spatial definition but the nature of this varies. Cluster M8 - and to some extent Cluster M7 - occupy relatively cohesive, adjoining fields, almost - but not quite - mutually exclusive. Most other clusters have looser fields which do not immediately adjoin one another, e.g. Clusters M5 and M6. Exceptions to this include: 1) Cluster M10 which has an intergrade position between Cluster M4 and Cluster M7: 2) the overlap in fields between Clusters M7 and M1: 3) the occurrence of Cluster M15 on one edge of Cluster M8: and 4) the occurrence of Cluster M11 on the opposite edge of Cluster M8.

Some of these distinctions can be made more specifically by cluster plots for the individual loaded variables. The plot for TC against NC63 (Figure 5B) shows clear spatial definition of most of the clusters and the following fairly specific relationships between clusters. For Clusters M1, M8, M7, M10 and M4, TC and NC63 are inversely proportional and this allows fairly sharp boundary definition, particularly for TC. Clusters M15 and M8 are separated at about 80% TC. A second cluster sequence includes Clusters M2, M5, M6, M9 and these, all with a low range of NC63 values, differ on TC, 20% separating Clusters M6 and M5. A third type of cluster sequence has constant TC values but variable NC63.

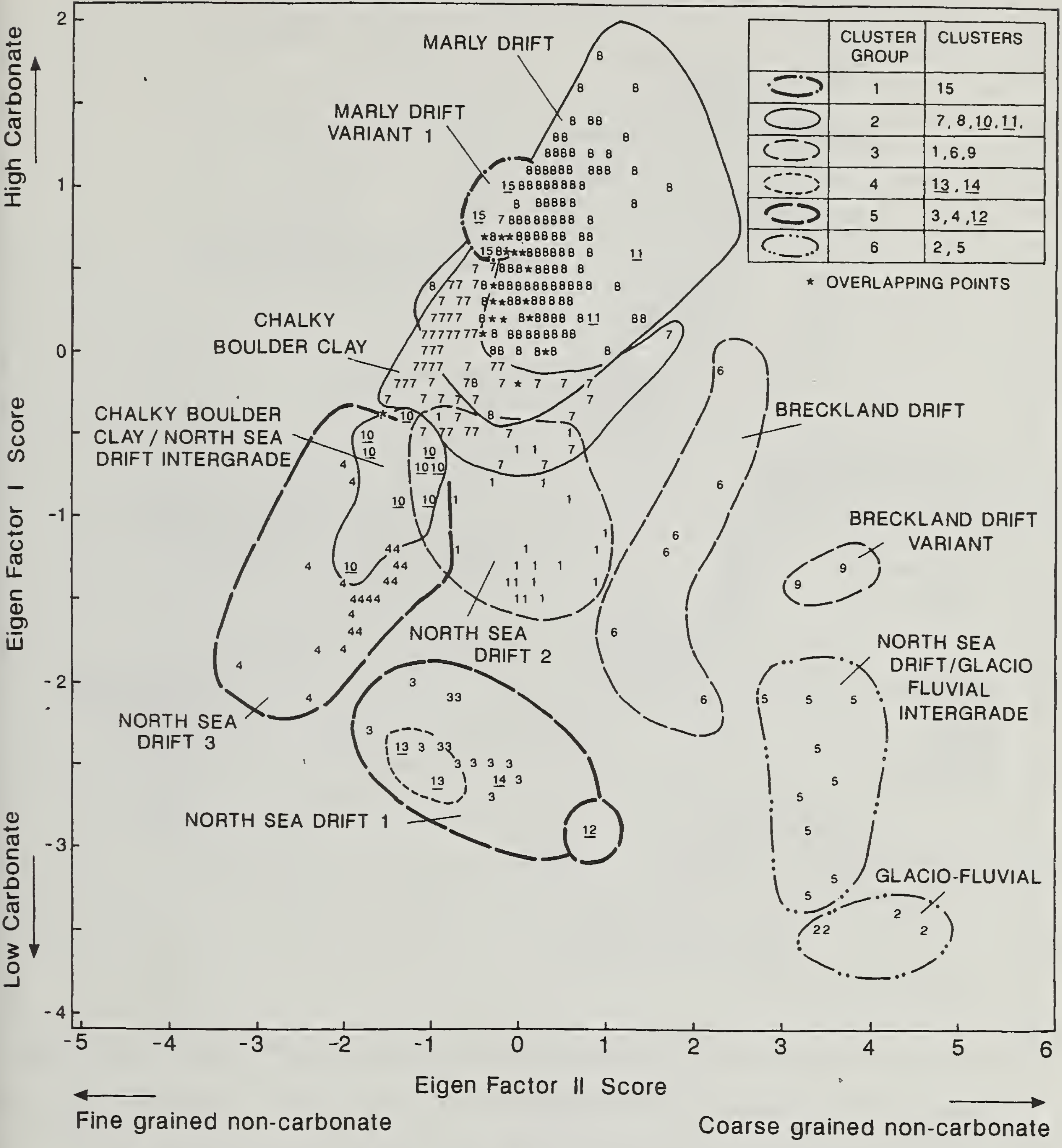


Fig. 5A. Measured Variable-derived cluster plot for Eigen Factors I and II.

For example, Cluster M1 with around 25% NC63, has more NC63 than Clusters M6 and M9 but less NC63 than Cluster M10.

The first two Eigen Factors derived from Principal Component Analysis of Ratio/Magnetism Variables are used to plot Ratio/Magnetism-derived clusters (Fig. 6). In contrast to the equivalent plots for Measured Variables in Figure 5A, individual clusters here have almost no spatial differentiation based on these two factors, which, as noted above,

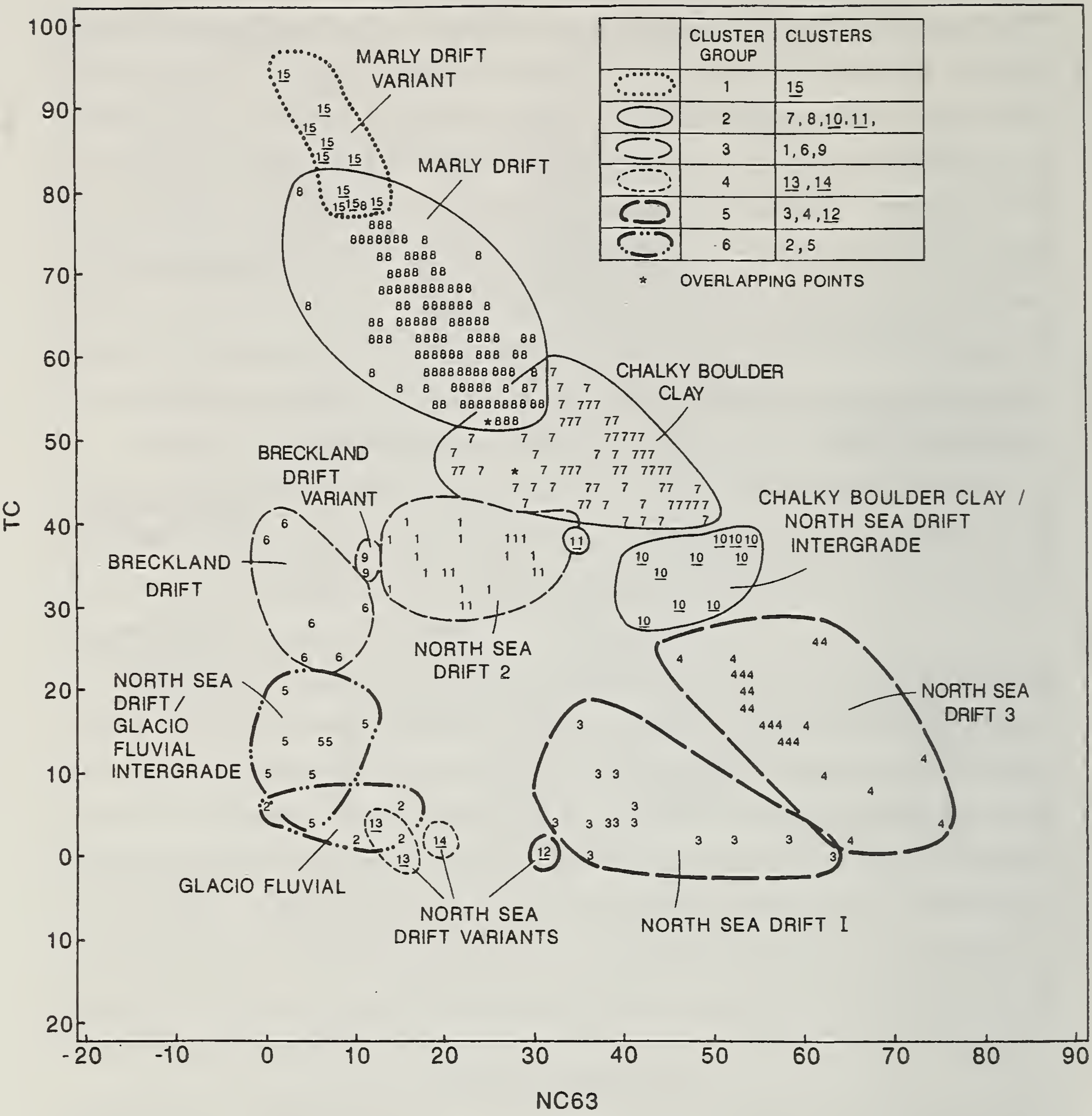


Fig. 5B. Measured Variable-derived cluster plot for loaded variables TC and NC63

describe the particle sizes of the non-carbonates and carbonates. For both Eigen Factors, Clusters R1 and R6 have a similar and relatively small range of values. This plots as a dense compact field, within which these two clusters - along with others - are thoroughly mixed. Outside this field the remaining clusters form a loose elongate spread. In this spread, although again the clusters are mixed, the mix for the higher positive Eigen factor values is mainly of Cluster R3 and R5. For negative values of Eigen Factor I and low positive values

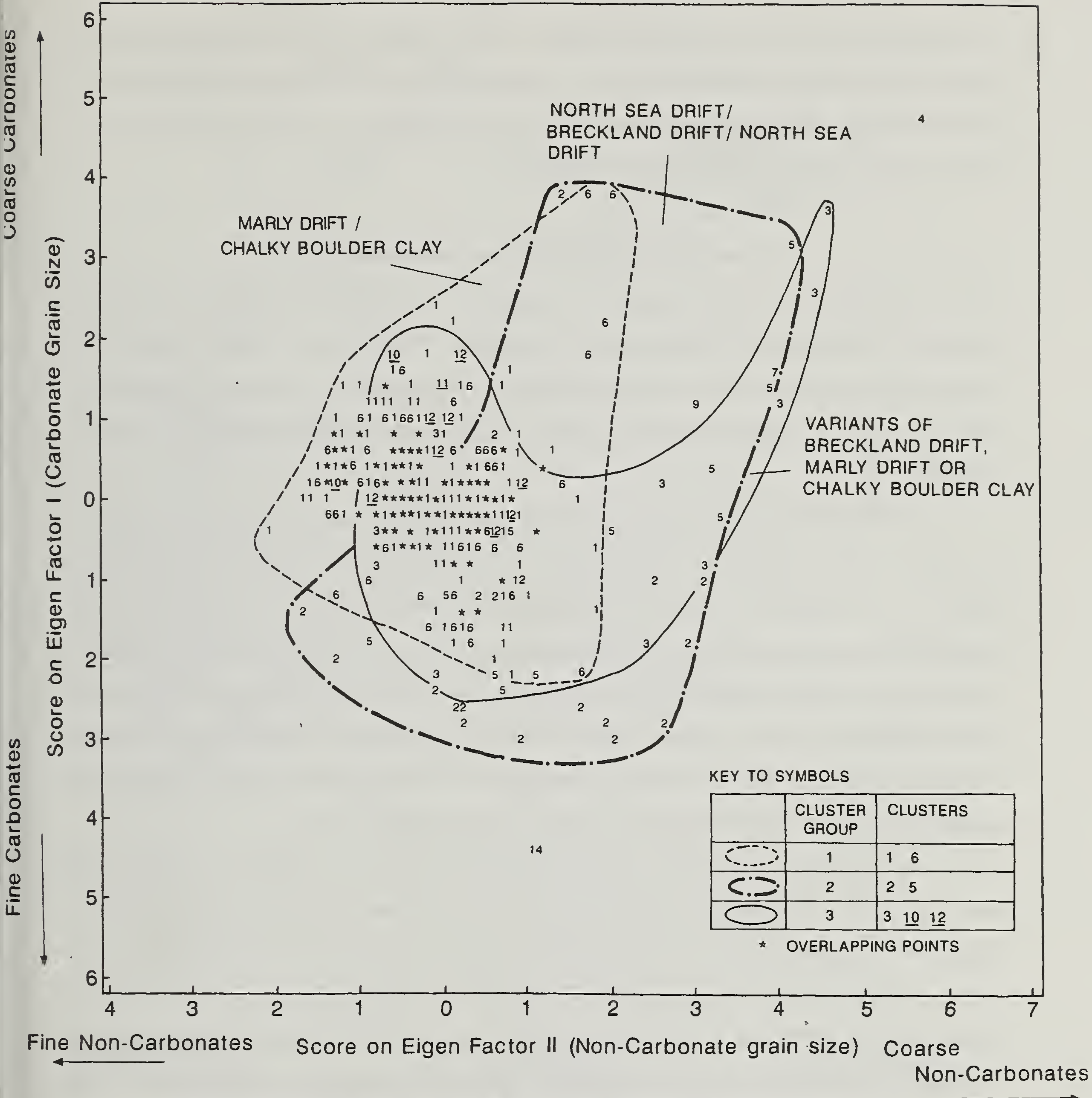


Fig. 6. Ratio/Magnetism-derived cluster plot for Eigen Factors I and II.

of Eigen Factor II, the mix is mainly of Clusters R2 and R5. In addition to these cluster groupings which have at least some spatial discrimination there are some points, peripheral to or distanced from these fields, with clusters from either grouping.

The loading of the variables in Eigen Factors I and II relates only to gross lithology. This analysis shows that, in contrast to the plots for Measured Variables, Ratio/Magnetism Variable plots, although having some spatial resolution for groupings of clusters, have little or no spatial resolution for individual clusters. This concurs with the findings based on Cluster Differentiation (outlined above). It suggests that the principal discrimination of Ratio/Magnetism-derived clusters is likely to be provided by the magnetic variables of Factors III and IV and the chalk content of Factor V.

Cross Matching and Cluster Nomenclature

Cross matching the clusters produced by analysis of Measured Variables with those produced by analysis of Ratio/Magnetism Variables (Table 10 and Fig. 7) shows that although direct equivalence between clusters does not occur there are varying degrees of partial equivalence. It also shows that almost complete equivalence of groupings of clusters occurs (Fig. 7).

Matching between the two sets of cluster groupings are shown separately in Figure 7 for clarity. This was achieved by enclosing the Measured Variable cluster number sequence between two sequences of the Ratio/Magnetism cluster numbers. Individual cluster matching between the central and the flanking number cluster sequences is shown by linkage lines and the numbers on these lines are the percentages of the total number of cases of the Ratio/Magnetism-derived clusters shared with the Measured Variable-derived clusters. From this point onward, for brevity, Measured Variable-derived cluster numbers are preceded by 'M' and Ratio/magnetism-derived cluster numbers by 'R'.

The main interacting clusters on the left hand side of Figure 7 are R1, R6, M7 and M8. 73% of the samples in Cluster R1 occur also in Cluster M8 and a further 20% in Cluster M7. Cluster R6 shares samples more equally with the same two M Clusters with further small sharing with Clusters M1, M10 and M15. Cluster R12 has similar links but here Cluster M8 makes by far the largest contribution. The situation on the right-hand side of Figure 7 is rather similar. Here Cluster R3 has some equivalence with Clusters M4 and M3 and Cluster R2 with Clusters M2, M3 and M4. Finally, Table 10 shows that Cluster R5 shares samples with Clusters M1, M6, M7 and M10 and also Cluster M1 with R1, R5, R6 and R10. The two sets of matching groupings in Figure 7 are almost entirely exhaustive (see Table 10), all other R-clusters containing only a handful of cases. Moreover, equivalence between certain individual M and R clusters can be near, or above, 50%.

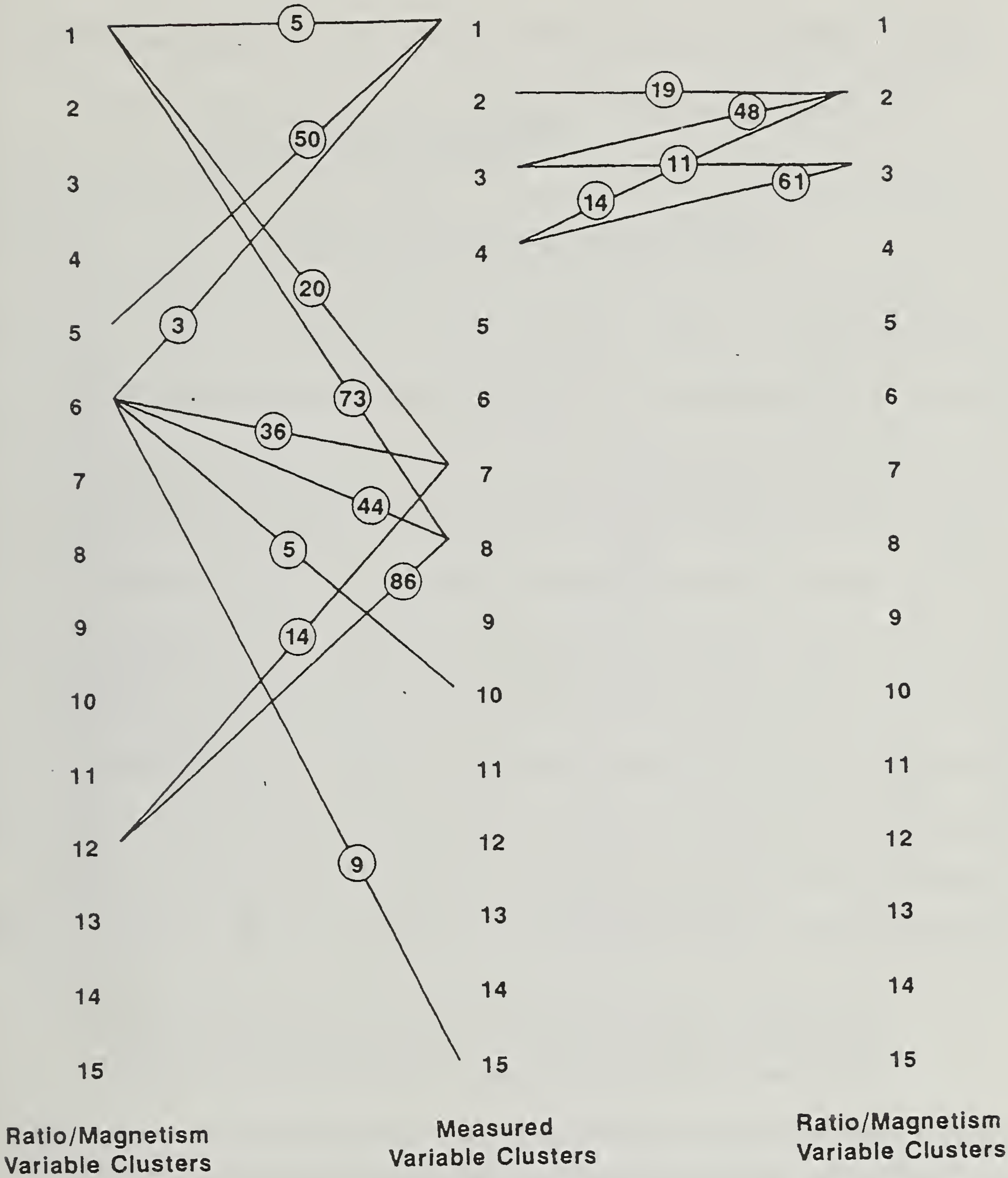

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Ratio/Magnetism Variable Clusters
Measured Variable Clusters
Ratio/Magnetism Variable Clusters
5
50
20
3
73
36
44
5
86
14
9
19
48
11
61
14

Fig. 7. Cluster matching percentages between Measured Variable and Ratio/Magnetism Variable classifications. Individual cluster matching between the central and the flanking number cluster sequences is shown by linkage lines. The numbers on these lines are the percentages of the total number of cases of the Ratio/Magnetism-derived clusters shared with the Measured Variable-derived clusters.

Table 10. Matching clusters derived from Measured and ratio/Magnatism Variables

RATIO

MEASURED

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Σ**	**%**
1	13				8	3										25	5.4
2		4														4	.9
3		10	3													13	2.8
4	2	3	17				1				1					24	5.2
5		3	4	1			1									9	2.0
6			1		4	1										6	1.3
7	52				3	27			1	2		3				98	21.4
8	187					45		1	1			18	1		1	254	55.3
9			1						1							2	.4
10	1		2		1	5										9	2.0
11						2										2	.4
13														1		1	.2
14		1														1	.2
15	2					9										11	2.4
Σ	257	21	28	1	16	10	2	1	3	3	1	21	1	1	1	**459**	
%	56.0	4.6	6.1	.2	3.5	22.2	.4	.2	.7	.7	.2	4.6	.2	.2	.2		**100**

Figures in boxes denote number of case that occur in both R and M clusters

Column and row totals and percentages are denoted **Σ** and **%** respectively

---

The matching of cluster groupings and individual clusters are used in Table 11 to compare lithologies. The variables used for comparison are those most heavily loaded in the Eigen Factors derived by Principal Component Analysis of both Measured and Ratio/Magnetism Variables. The values of variable means in Cluster M1 and Cluster R5 are certainly comparable (Table 11). This also applies (centre of the Table 11), to Clusters R1, R6 and R12 and Clusters M7 and M8. The differences in TC and NC63 between Clusters M7 and R6 have particular importance (see below). In the bottom section of Table 11 there is close linkage between Clusters M3 and R2 and between Clusters R3 and M4. The various

Table 11. Lithological comparison between matching cluster groupings and between matching clusters.

(Variable abbreviations are defined in Table 1)

	TC	C63	C>250	C>500	NC63	NC250	NC>250
1M	35.3 ±3.3	31.7 ±3.3	1.9 ±1.3	1.5 ±1.1	23.0 ±5.5	25.7 ±5.9	15.9 ±5.2
5R	35.8 ±5.5	29.6 ±6.9	3.9 ±3.1	3.3 ±2.8	22.4±15.1	27.3±11.6	14.6 ±7.5
1R	58.2±10.5	48.8 ±9.1	6.6 ±2.6	5.6 ±2.4	24.7 ±9.4	9.5 ±4.8	7.6 ±3.5
8M	63.5 ±6.4	53.2 ±6.1	7.2 ±2.5	6.1 ±2.3	20.1 ±4.9	8.8 ±2.4	7.7 ±2.6
6R	57.4±14.9	48.7 ±14.6	6.2 ±3.1	5.2 ±2.9	25.3±12.3	9.2 ±4.3	8.0 ±4.7
7M	47.4 ±4.4	39.3 ±3.8	5.8 ±1.9	4.9 ±1.8	37.3 ±6.8	8.7 ±3.2	6.6 ±3.8
12R	61.7 ±9.0	51.7 ±8.6	6.9 ±2.3	5.6 ±2.0	20.3 ±6.7	9.5 ±3.1	8.5 ±3.7
3M	4.6 ±4.2	4.3 ±4.1	0.2 ±0.2	0.1 ±0.2	42.4 ±9.1	33.5 ±8.4	19.5 ±5.0
2R	5.2 ±4.0	4.7 ±3.6	0.2 ±0.3	0.1 ±0.2	32.4±23.2	31.7±12.5	30.7±22.8
3R	17.4 ±7.7	14.3 ±6.5	2.1 ±1.4	1.7 ±1.3	42.9±20.8	21.2 ±8.1	18.5±15.2
4M	16.7 ±6.5	13.9 ±5.3	1.7 ±1.1	1.4 ±1.0	58.0 ±6.7	16.9 ±4.4	8.4 ±2.4

percentage values for these cluster pairings are in good agreement. In both these cluster pairings, linkage is weakest for NC63 and NC>250. Table 12 matches the two Cluster Analysis classifications to the individual samples taken at the reference sites.

For Measured Variable-derived clusters there is an almost perfect consistency within sites and on this basis Cluster M7 can be identified with the Chalky Boulderclay (CBC), Cluster M6 with the Breckland Drift (BR), Cluster M3 with the First Cromer Till (NSD1), Cluster M1 with the Second Cromer Till (NSD2), and on the basis of the single reference sample from West Runton, Cluster M4 with the Contorted Drift (NSD3).

Table 12. Cluster matching of drifts from reference sites

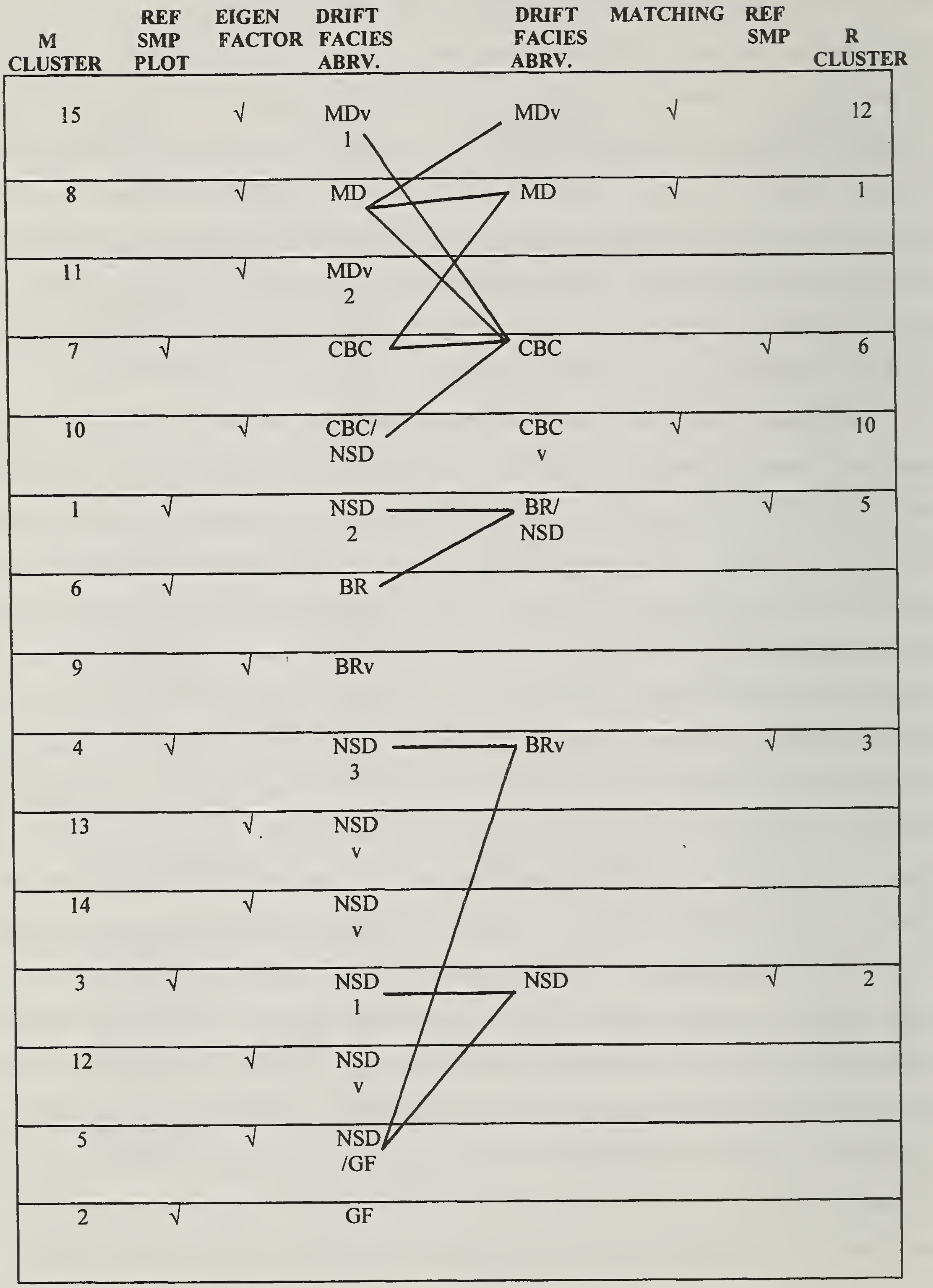
Location	**Site No.**	**Measured Variable Cluster**	**Ratio/Mag. Variable Cluster**
Gt. Blakenham		***Chalky Boulderclay***	
TM100503	386	7	6
"	387	7	6
TM108504	388	7	1
"	389	7	6
"	390	7	10
"	391	7	-
Breckland		***Breckland Drift***	
TL806837	384	8	1
TL810836	385	6	3
TL822839	385/1	6	5
"	385/2	6	5
TL828901	385/3	6	5
"	385/4	6	5
N. E. Norfolk		***North Sea Drifts***	
Happisburgh	378	3	2
TG383312	379	3	2
Mundesley	380	1	6
TG301377	381	1	10
Overstrand	382	1	5
TG248411	383	1	5
West Runton TG192430	383.1	4	1

When these clusters are located on the Eigen Factor plots (Fig. 5A) they provide a framework for assigning names to the remaining clusters. All of the clusters named above have significant numbers of cases, yet Cluster M8, with by far the largest number of cases, (254), remains unnamed. This cluster immediately adjoins Cluster M7 (CBC) in Figure 5A, indicating close taxonomic association. The lithological characters of M7 and M8 (Table 11) show that Cluster M7 (CBC) has 47.4% TC and 37.3% NC63 while Cluster M8 has 63.5% TC and 20.1 NC63. This clear difference is also apparent in Figure 5B, strongly suggesting that Cluster M8 can be classed as Marly Drift, and renamed Cluster M8 (MD). The Eigen Factor plots show also that Clusters M15 (Fig. 5A) and M11 (Fig. 5A) are closely associated with Cluster M8 (MD) and on this basis are classed as Marly Drift variants, Cluster M15 (MDv) and Cluster M11 (MDv2).

Working in the same way from named clusters, Cluster M10 (Fig. 5A) is an intergrade between Cluster M4 (NSD3) and Cluster M7 (CBC) and as such is named Cluster M10 (CBC/NSD). Clusters M12, M13 and M14 (Fig. 5A) are associated with Cluster M3 (NSD1) and as such, and because they have very few cases, they are lumped together as variants of the North Sea Drift (NSDv). Of the remaining clusters M2 includes a sample from the glacio-fluvial outwash at the base of a drift exposure on Flordon Common (TM 193991), and on this basis - and because of its coarse non-carbonate grain size and low carbonate content - is named, Cluster M2 (GF) [i.e. glacio-fluvial]. Cluster M5 lies between Cluster M2 (GF) and the general location of the North Sea and Breckland drift facies (Fig. 5A) and is thus classed an intergrade, Cluster M5 (NSD/GF). Finally, Cluster M9 with 2 cases is, if anything, most closely associated with Cluster M6 (BR) and on this basis is classed a variant, Cluster M9 (BRv). A full list of cluster nomenclature is given in Table 13.

The Ratio/Magnetism cluster classification for the reference samples (Table 12) is quite complex. Although there is some within site consistency, there is also within site differentiation and, rather surprisingly, some between site matching. Within site consistency indicates that Cluster R6 contains the reference samples of Chalky Boulderclay (Cluster R6 (CBC)); that Cluster R2 contains the First Cromer Till (Cluster R2 (NSD)). Cluster R5 contains the Second Cromer Till; however it also includes most of the Breckland Drift samples and for this reason Cluster R5 is classed an intergrade (Cluster R5 (NSD/BR)).

Table 13. Cluster nomenclature and its sources



M CLUSTER	REF SMP PLOT	EIGEN FACTOR	DRIFT FACIES ABRV.	DRIFT FACIES ABRV.	MATCHING	REF SMP	R CLUSTER
15		√	MDv 1	MDv	√		12
8		√	MD	MD	√		1
11		√	MDv 2				
7	√		CBC	CBC		√	6
10		√	CBC/ NSD	CBC v	√		10
1	√		NSD 2	BR/ NSD		√	5
6	√		BR				
9		√	BRv				
4	√		NSD 3	BRv		√	3
13		√	NSD v				
14		√	NSD v				
3	√		NSD 1	NSD		√	2
12		√	NSD v				
5		√	NSD /GF				
2	√		GF				

The Breckland Drift reference samples also include Cluster R3 and, on a single sample, this is classed a variant (Cluster R3 (BRv)). The remaining reference samples are classed in either Clusters R1 or R10.

The Eigen Factor plot (Fig. 6) indicates that Cluster R1 is closely associated with Cluster R6 (CBC) but the plot does not provide clear spatial definition in the way the Measured Variable derived clusters do. This limitation is particularly true for clusters not covered by reference samples. Fortunately, such clusters have very few cases (most of them only one).

The number of cases in Cluster R1 (257), is closely comparable with the 254 cases in Cluster M8 (MD) and matching these (Table 10 and Fig. 7) shows that more than 70% of the samples in the latter occur also in the former. On this basis Cluster R1 is classed as Marly Drift (Cluster R1 (MD)). Similarly, 2 out of the 3 cases of Cluster R10 are classed alternatively as Cluster M7 (CBC) and on this basis Cluster R10 is classed a variant (Cluster R10 (CBCv)). The one Ratio/Magnetism-derived cluster outside the reference samples in this cluster is classed alternatively as Cluster M8 (MD) and on this basis the cluster is classed a variant (Cluster R12 (MDv)). Table 13 summarises the stages in applying nomenclature to the units derived from the two forms of Cluster Analysis.

Having applied traditional terminologies that distinguish, within classifications, the individual drift facies and their equivalence between the classifications, an important point needs emphasising. In spite of cross cluster equivalence and the marked difference in mean TC values between Cluster M7 (CBC) and Cluster M8 (MD), 47.4% and 63.5% respectively, the TC means for Cluster R6 (CBC) and Cluster R1 (MD) are much closer, 57.4% and 58.2% respectively. Thus, the Measured Variable-derived clusters appear to discriminate much more successfully than the Ratio/Magnetism-derived clusters, the lithological differences between these two drift facies.

Once again it appears that much of the discrimination by individual variables between R clusters may lie in the magnetic variables rather than the particle size and carbonate content variables discussed so far. Therefore, the R cluster classification and especially its postulated equivalence with previously recognised mappable units among the East Anglian tills, must be employed with great caution. Likewise, the gross lithology brought out by the M cluster analysis, appears to identify traditional mappable units rather well. However, gross lithology alone may be insufficient evidence for the ***origin*** of a till, and the magnetic variables included in the R cluster analysis may provide extra information in this regard.

DISCUSSION AND CONCLUSIONS

Lithology of Drift Facies Derived from Measured Variables

Eigen Factor plots and certain key variable plots (Figures 5A and B) show fairly clear separation of two groupings of drift facies and, within these, of individual drift facies. For most of the key variables, sequences of drift facies ordered by their mean values can be subdivided into three broadly similar groupings (Table 4). Within and between these facies groups, differentiation of most individual drift facies (Table 5), can be based on at least one of two key variables (TC and NC63) and exceptions concern drift facies with only two cases. This suggests that in general, Cluster Analysis differentiates the gross lithology of major drift facies.

This method of classification also distinguishes clearly the traditional till units – based on samples from reference sites (Table 12). At Great Blakenham all of the Chalky Boulderclay samples are classified as members of a single facies. Moerover, and in agreement with Allen (1984), Baden Powell's Gipping Till was not differentiated in the immediate sub-surface on slopes. In Breckland, the more chalky drift on slopes (Cluster M8 (MD)), with a mean TC of 65.5%, is differentiated from the less chalky drift on the plateau (Cluster M6 (BR)), with a mean TC of 30.3%. It should be noted, however, that Cluster M6 (BR) has in total only six cases, five of these being on the Breckland plateau and the remaining one, at depth, towards the lower slope, at Flordon.

In north east Norfolk, the First Cromer Till (Cluster M3 (NSD1)) at Happisburgh is differentiated from the Second Cromer Till (Cluster M1 (NSD2)) at Mundesley. However, the samples from Overstrand, which according to Ranson (1967) and Banham (1975) should have come from the Third Cromer Till, are classed in the same unit as the Second Cromer Till. Indeed their similar TC values (37.2% and 36.5%), seem to confirm this. This means that in this study there is no differentiated representative of the Third Cromer Till, suggesting it was not correctly located during field sampling. However, the Contorted Drift sample from West Runton is classed in a separate unit (Cluster M4 (NSD3)).

Comparisons in gross lithology between the major drift facies defined earlier and in this study are shown in Table 14. To allow comparison, several of the particle size fractions

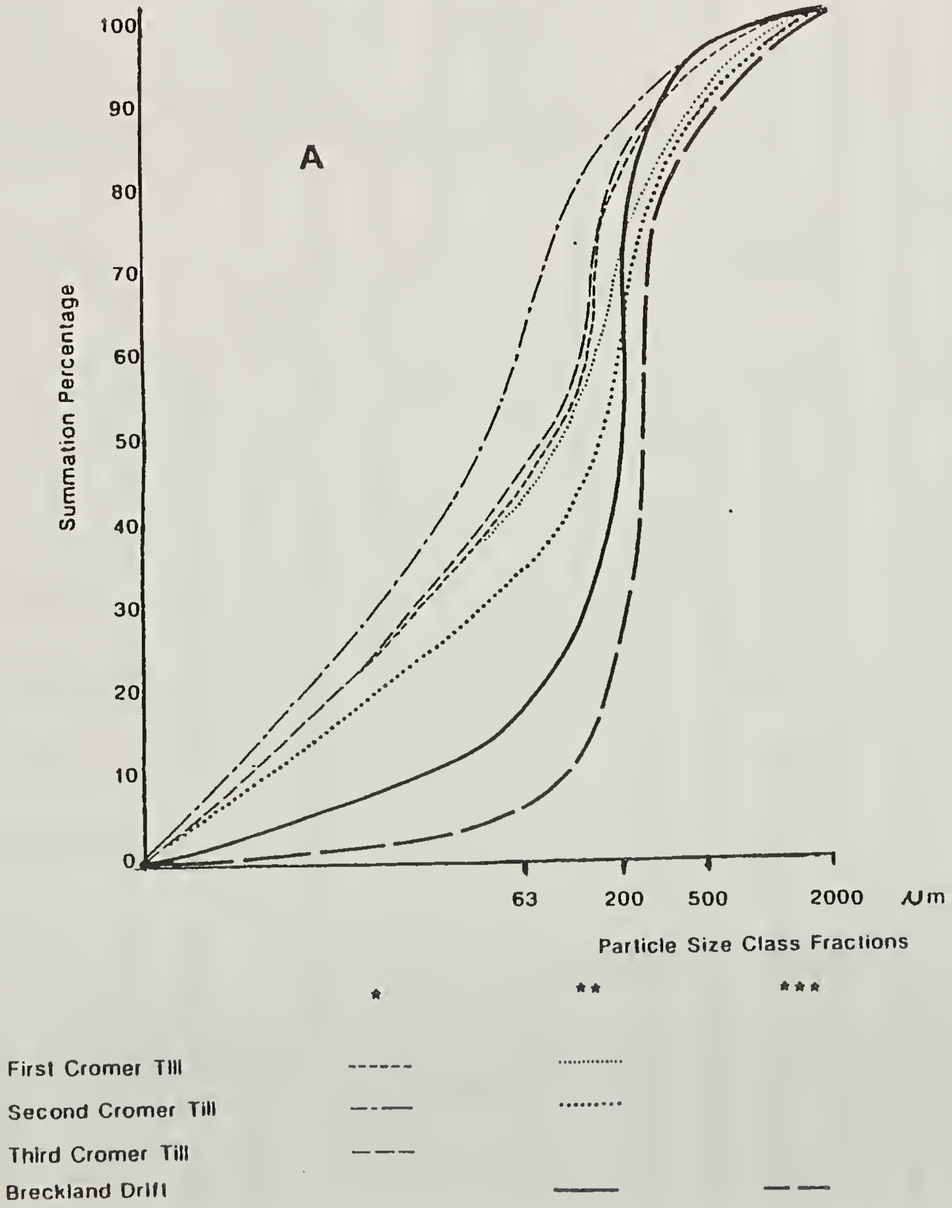
Table 14. Gross lithology of major drift facies as defined by Perrin *et al.*(1979)*, this study** and the Soil Survey of England and Wales (SSEW)***.

	Mean TC		**2mm-500µm**	**>500µm**	**500-210µm**		**210-63µm**		**<63µm**	
	*	**	*	**	*	**	*	**	*	**
Chalky Boulderclay	40	(47.4)	2.5 *	(5.5)	6.5	(7.0)	13.5	(16.5)	77.6	(70.9)
Marly Drift (CBC)	72	(63.5)	3.4 *	(8.8)	8.3	(12.3)	17.2	(24.1)	71.3	(55.1)
Marly Drift (NSD)	44	(84.1)	4.8	(12.0)	17.5	(14.5)	31.2	(25.9)	46.6	(47.2)
First Cromer Till	8	(4.6)	2.9	(7.2)	13.0	(13.2)	39.3	(35.1)	44.9	(44.4)
Second Cromer Till	34	(35.3)	1.9	(9.3)	7.8	(15.3)	28.8	(39.7)	61.3	(35.5)
Third Cromer Till	9	-	1.2	-	11.8	-	39.2	-	46.7	-
Contorted Drift	11	(16.7)	2.4	(4.6)	9.8	(5.5)	40.8	(20.3)	47.3	(69.6)
	***		***		***		***		***	
Breckland Drift	31.7	(30.3)	2.4	(10.8)	26.1	(27.1)	56.1	(54.9)	15.5	(7.3)

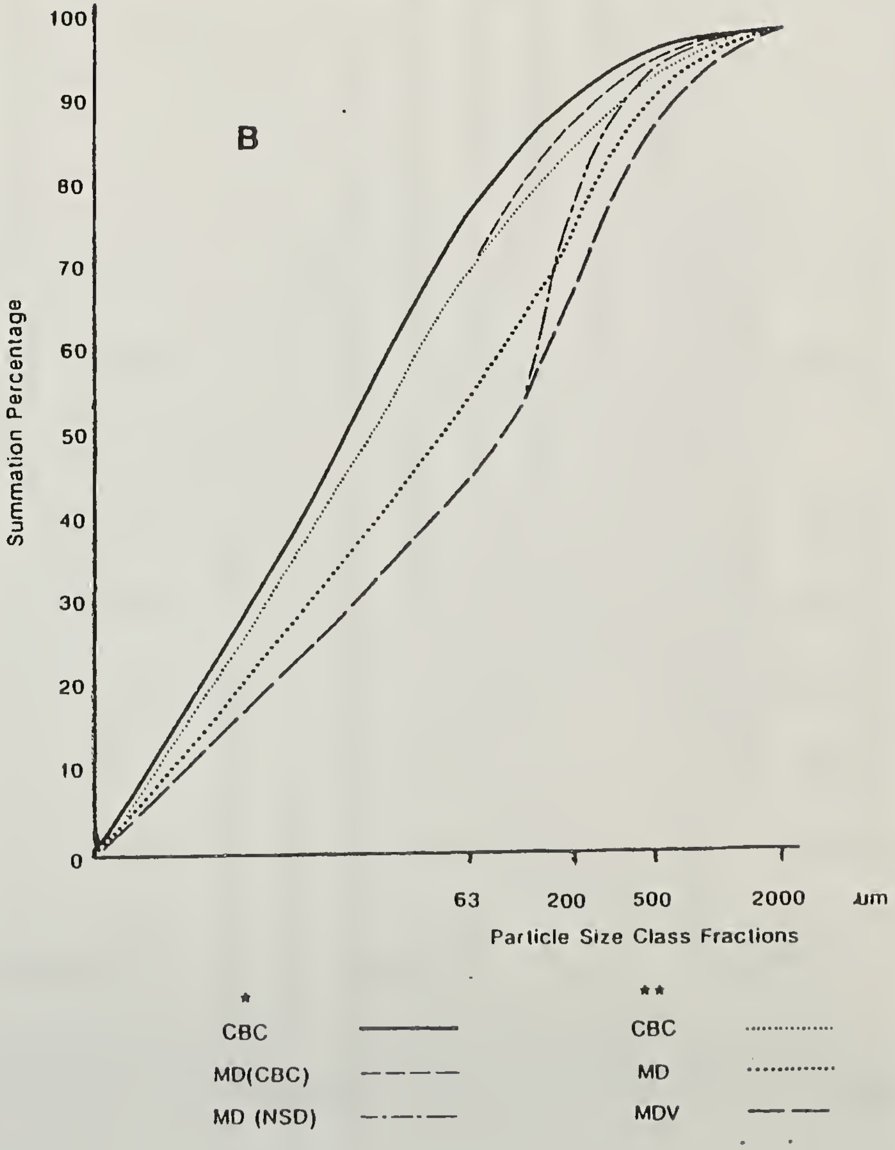
Exact Particle Size-Class FractionsUsed in Each Study

* Perrin *et al.*(1979)	** This Study	*** SSEW
500µm-2mm	> 500µm	> 500µm
210-500µm	250-500µm	200-500µm
63-210µm	63-250µm	50-200µm
< 63µm	< 63µm	< 50µm

A) North Sea and Breckland Drifts



B) Chalky Boulderclay and Marly Drift



used by Perrin *et al.* (1979), were amalgamated. The table also includes Norfolk Chalky Boulderclay and Breckland Drift data from the Soil Survey of England and Wales (SSEW). Note, however, that the earlier data deal only with the matrix material of <2 mm (see Methods). Clearly, omission of the coarser material when using a percentage scale, exaggerates the values of the finer fractions relative to the present study. Also, some of the size class fractions used in the separate studies do not coincide (see Methods). The upper limit for the fine sand fraction was 210 µm in Perrin *et al.* while the SSEW used an upper limit of 200 µm rather than the 250 µm used in this study. Furthermore the upper limit of the silt fraction used by the SSEW was 50 µm rather than the 63 µm limit used by Perrin *et al.* (1979) and this study. This second problem has been avoided to some extent by using particle size class summation curves (Fig. 8).

The cut-off of sampled particles at an upper size class of 2 mm (Perrin *et al.*, 1979 data) distorts the TC values in particular. This occurs because the carbonate particle size distribution is distinctly bimodal in the Lowestoft Till, the coarser mode coinciding approximately with the 2 mm limit (Perrin *et al.* 1979). This may account for the lower carbonate values of drift facies in Perrin *et al.* (1979) and in Table 14. The main exception to this distortion is in the Perrin *et al.* (1979) Marly Drift (Lowestoft Type). The higher carbonate values in this facies, taking into account the 254 cases in the present study compared to just 15 in Perrin *et al.* (1979), may indicate a bias in their "allocation of samples to particular units by subjective field criteria" (Perrin *et al.* 1979).

It is clear in Figure 8 that the 2 mm limit in Perrin *et al.* data, and in the SSEW data, give them in most cases, higher values on the ordinate than the curves from the M-cluster units defined in the present study. However, in spite of the differences in analytical method the major drift facies have distinctive cumulative particle size curves (Fig. 8). In the Chalky Boulderclay curve there is no point of inflexion, whereas in the Breckland Drift inflexion is marked; in the North Sea Drifts, the First Cromer Till, shows an intermediate degree of inflexion. The distinctness of the curves generated by independent studies suggests that there is at least some equivalence between units in the different classifications.

Fig. 8. (Opposite page). Particle size class summation curves derived from the present and earlier work. * = data from Perrin *et al.* (1979); ** = data from this study; *** = data from Soil Survey of England and Wales (Corbett (1973).

Lithology of Drift Facies derived from Ratio/Magnetism Variables

Eigen Factors indicate, to some extent, two groupings of R clusters: one represents a 'Lowestoft Till' group of tills and the other the Breckland and North Sea Drifts. Within the former there is no clear separation of individual drift facies and, in the latter, only a very limited degree of differentiation.

The lack of differentiation of individual Ratio/Magnetism-derived drift facies is clear in Table 6 where sequences of drift facies for each of the key variables are ordered by the values of their means. Although these sequences can be subdivided into three groups – with some consistency of group definition between variables for both the carbonate and the non-carbonate variable sequences - within these groups the mean values are tightly clustered and standard deviations overlap broadly. Unlike the clear differentiation of most of the drift facies derived from measured variables (Table 5), there is poor differentiation in the sequences of means of the key variables (C>250, C63 and NC63) based on Ratio/Magnetism-derived units (Table 7). Differentiation of gross lithology is thus based not on individual variable values, but on their amalgamated influence in the individual Eigen Factors or Principal Components. In other words, no individual variable of the gross lithology differentiates all of the major drift facies. A corollary of this finding is that, certainly for the 'Lowestoft Till' group of Ratio/Magnetism-derived drift facies, the gross lithologies of the individual facies are so alike that they cannot be used for lithogenic interpretation.

There are two important final points. In the Measured Variable classification the intergrade unit Cluster M10 (CBC/NSD) links the two major drift groupings, and in the Ratio/Magnetism classification the intergrade unit Cluster R5 (BR/NSD) links the Breckland and North Sea Drifts.

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APPENDIX 1

CLUSTER ANALYSIS AND PRINCIPAL COMPONENT ANALYSIS

Cluster Analysis

Cluster Analysis is a statistical technique for recognizing and defining natural grouping or clusters within data sets (Manly 1990). Cluster definition is based on the relative difference or distance between sample values. For one variable this can be expressed as a simple linear measurement, for two or more variables it is the Euclidean distance with each variable representing an axis in multidimensional space. Figure 9 shows the Euclidean distance between two samples for three variables, X1, X2, X3 and Pythagoras' Theorem gives the distance as:

$$dij = \sqrt{\{\sum_{k=1}^{3}(Xik - Xjk)2\}}$$

For more than three orthogonal variables the general equation for Euclidean distance is:

$$dij = \sqrt{\{\sum_{k=1}^{p}(Xik - Xjk)2\}}$$

In these equations *i* and *j* are individual samples, *k* is the variable, and *p* is the number of variables.

As with Principal Component Analysis (see below), variables are standardized to avoid domination of one or two variables due to large numerical differences in scales of measurement. In standardised form, the value of each variable is subtracted from the mean and divided by the standard deviation. For the i^{th} variable and j^{th} sample out of N samples, the standard form of variable i for sample j is:

$$\frac{(\text{measured value})\ ij - \text{mean } i)}{\text{Standard deviation } i}$$

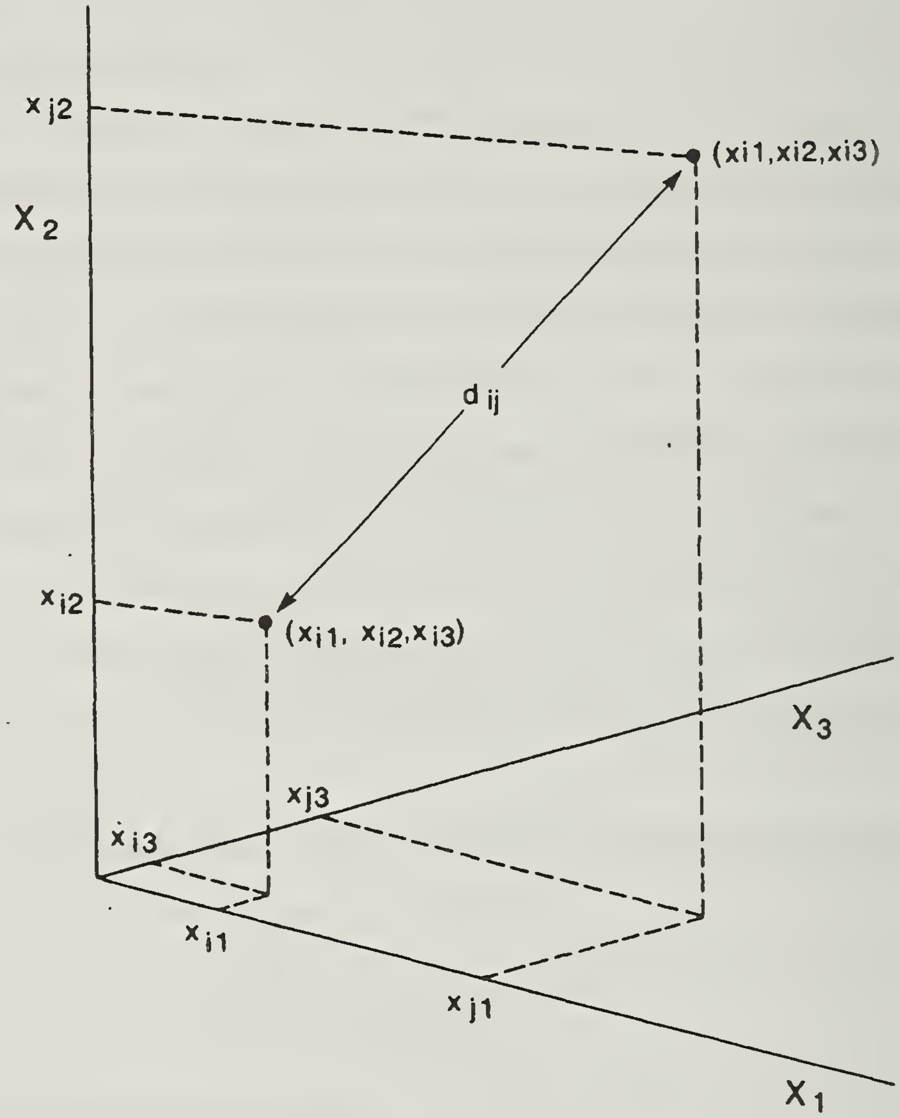

Fig. 9. The Euclidean distance between individuals i and j with $p = 3$ variables.

Principal Component Analysis

In Principal Component Analysis the standardized values of individual variables are plotted in a multidimensional variable space, the angles between the variables being determined by their correlation structure. The cosine of the angle between two variable axes is made equal to the correlation coefficient, 'r', between them in the sample data. The correlation matrix of the data thus defines all the angles between all possible pairs of variable axes. Only one geometric arrangement of variable axes will satisfy all these angles and this arrangement defines the variable space. The sample points plot as a cloud in this space, the cloud showing elongation in certain directions and flattening in others depending on the correlation structure of the sample. The process of selecting Eigen Factors or Principal Components is one of identifying new orthogonal variables, the number being equal to the number of the original variables. The axis of the first principal component is selected so as to minimise the sum of squares of deviations of data points from the axis itself. A second principal component is then selected, at 90 to the first, so as to minimise the sum of squares of residuals between the sample points and the plane formed by the two principal components. Further principal components are determined in a similar way until the same number of principal components as there were original variables have been defined. These principal components now constitute a new set of compound variables which together describe the data as completely as the original variables. The angles between the principal components and the original variables define the correlations between each variable and each principal component in turn. These correlations constitute the Factor Matrix or Factor Loading Matrix. Factors with a high loading for a variable are highly correlated with that variable.

Considering in turn the proportion of the total variance explained by each principal component, a relatively small number of principal components may explain most of the variance in the original data, the small proportion of variance explained by the remaining principal components being considered as random noise.

Editor's Note

As the pre-Devensian till stratigraphy of North-East Norfolk is potentially confusing, the following table and notes might help readers clarify and compare the various units referred to in the papers by Corbett (this Bulletin). The table below outlines four schemes. Corbett has used the classification of Banham (column 1).

Banham (1968; 1988)	**Hart & Boulton (1991)**	**Lunkka (1994)**	**Hamblin *et al.*, (2000)**
Lowestoft Till (= Marly Drift)		Lowestoft Till Formation Marly Drift Member	
Third Cromer Till	Walcott Diamicton Member	Cromer Diamicton Member Mundesley Diamicton Member	Overstrand Formation Hanworth Till Member
Second Cromer Till	Eccles Diamicton Member	Walcott Diamicton Member	Lowestoft Formation Walcott Till Member
First Cromer Till	Happisburgh Diamicton Member	Happisburgh Diamicton Member	Corton Formation Happisburgh Till Member

Notes: The First, Second and Third Cromer Tills (column 1) are traditionally regarded as the North Sea Drift (Formation). Acceptance of the Hamblin *et al.*, (2000) scheme would negate this as they do not regard the Walcott Till as one of the North Sea Drifts. However, the Hamblin *et al.*, (2000) stratigraphy is controversial, and Banham *et al.*, (2001) urge retention of the Lowestoft Till (Formation) and North Sea Drift (Formation) as used by Corbett in this Bulletin. Note also that the 'Walcott Diamicton Member' of Hart and Boulton (1991) is a different unit to that of Lunkka (1994).

Further details, debate and full references can be found in Hamblin *et al.* (2000, *Quaternary Newsletter*, **92**, p. 35-43) and in Banham *et al.* (2001, *Quaternary Newsletter*, **93**, 5-14).

STRATIGRAPHY OF THE EAST ANGLIAN CHALKY BOULDERCLAY PLATEAU BASED ON STATISTICAL DIFFERENTIATION OF TILL FACIES

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ABSTRACT

This paper analyses stratigraphically the results of two forms of Cluster Analysis used to differentiate between lithologies and facies of the Chalky Boulderclay in Norfolk and Suffolk (Corbett 2001). The primary aim is to establish the local stratigraphy for borehole sites on the Chalky Boulderclay plateau. Stratigraphic sections of the boreholes deeper than 20 m show a marked contrast in pattern between facies derived from Cluster Analysis of Measured Variables (M clusters) and those derived from Ratio/Magnetism variables (R clusters). M clusters show no obvious stratigraphic pattern. In contrast, R clusters identify a fairly consistent set of units. An upper unit – predominantly Marly Drift, a lower unit – predominantly of Chalky Boulderclay, and a middle unit – a variant of the Marly Drift with inclusions of Chalky Boulderclay. A distinguishing feature of the Marly Drift variant is the high concentration of magnetic minerals.

INTRODUCTION

Recently, Cluster Analysis and Principal Component Analysis have been used to differentiate between lithologies and facies of the Chalky Boulderclay in Norfolk and Suffolk (Corbett 2001). These statistical analyses were applied to carbonate and non-carbonate particle size data and also to magnetic characteristics of the non-carbonate fine sand (63-250 µm) fraction. The particle size data were used in two forms. First, the individual fractions, carbonate and non-carbonate, were expressed as percentages. In the second, the individual fractions were expressed as ratio percentages of the total carbonate

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and non-carbonate fractions. Initially the magnetic measurements were included only in the second form (Corbett 2001). Cluster Analysis was then applied to both forms of data to recognize and define discrete groupings or facies, while Principal Component Analysis was used to recognise the key discriminating variables.

Facies identified by Cluster Analysis from the data in the single percentage data were referred to as the Measured Variable or M clusters and termed lithologic units. Facies recognised in the Ratio/Magnetism-derived percentage data were referred to as 'R' clusters and termed lithogenic units (Corbett 2001). The M clusters were clearly defined and easily matched to the reference samples of the various East Anglian drifts. While the R clusters did differentiate between the North Sea Drift group and the Chalky Boulderclay group, within these groupings individual facies were poorly differentiated.

This paper analyses the results of the two forms of Cluster Analysis classification in the context of the field location of the samples, the primary aim being to establish the local stratigraphy for each drill site on the Chalky Boulderclay plateau. The various cluster numbers (M7, R6 etc) used in this paper are taken from Corbett (2001), where the derivation is described in detail.

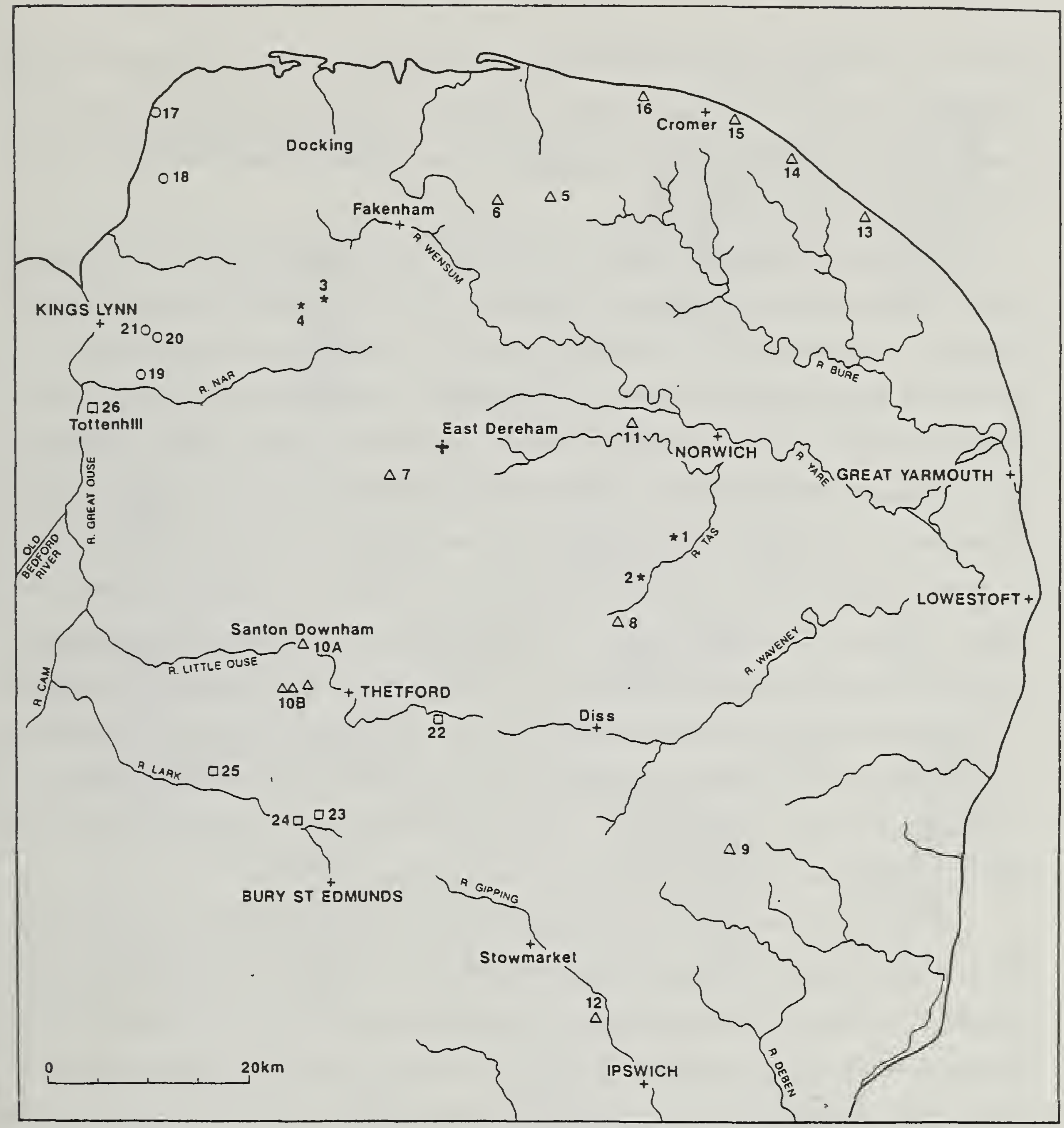
SPATIAL TILL FACIES DISTRIBUTION

The location of all sampling sites, the relief transects near the plateau perimeter in east and west Norfolk, the individual drill sites on the central plateau, and the reference sample exposures, are detailed in Corbett (2001) and shown in Figure 1. Full details of sampling and laboratory methods are also given in Corbett (2001).

Local (km) Scale Distributions

The transect relief sections at Flordon, Bunwell, Rougham and Weasenham (see also Corbett 2001), are given in Figures 2A, 2B, 2C and 2D respectively. The relief section in each figure shows separately the stratigraphic pattern for the two forms of cluster classification, M and R clusters.

The pattern of till facies in all four transects is complex, but close inspection suggests that there are three major elements common to all. These are: 1) the consistent stratigraphy of the R Clusters 'Lowestoft Till' group of drift facies as shown by the deeper drillings on central interfluve sites; 2) the relation of this group to the distribution of Breckland (BR) and



★ Transects
△ Individual Cores and Sampling Points
☐ 1991 Q.R.A. Excursion Sites
○ Lower Cretaceous Sands

1 Flordon
2 Bunwell
3 Weasenham
4 Rougham
5 Briston
6 Swanton Novers
7 Shipdam
8 Winfarthing
9 Tannington
10A Breckland North
10B Breckland South
11 Hagg's Pit Easton
12 Great Blakenham
13 Happisburgh
14 Mundesley
15 Overstrand
16 West Runton
17 Hunstanton
18 Snettisham
19 Blackborough End
20 Golf Course Pit
21 Bawsey Pit
22 Knettishall
23 Ingham
24 West Stow
25 High Lodge
26 Tottenhill

Fig. 1. Map of the main sampling locations.

North Sea Drift (NSD) drift facies (M and R Clusters) as shown particularly by the stratigraphy on lower slopes; and 3) the occurrence of the same drift facies (M and R Clusters) near the ground surface on middle and some upper slopes with facies of the 'Lowestoft Till' group at depth.

The general stratigraphy of the 'Lowestoft Till' group facies in the deeper borings on central interfluve sites is summarised in Figure 3. The four profiles are, on the Bunwell transect at site numbers 15 (TM104934) and 28 (TM122936), at Rougham site 35 (TF832213) and at Tannington, site 43 (TM250692). Vertical profiles based on the R-derived drift facies, have a common feature in possessing three fairly distinct stratigraphic units. In Figure 3 this is best shown in the profile on site 28 (Bunwell). The upper unit here is predominantly Cluster R1 (Marly Drift - MD) and the lower one predominantly Cluster R6 (Chalky Boulder Clay - CBC). The middle unit is a mixture of Cluster R12 (Marly Drift variant - MDv) and Cluster R6 (CBC). To varying degrees this stratigraphic arrangement is also shown by the other three profiles (Fig. 3). Accepting this, a re-examination of Figures 2A to D shows, that with some exceptions, most of the shallower profiles in the transect sections and the deep profile at Weasenham, site 36 (TF869214) can be interpreted as the upper part of this three unit sequence. The spatial relationship of these units across the plateau in Norfolk and Suffolk is shown in a 'fence' diagram in Figure 4.

When M-derived clusters are considered, the vertical profiles for the four sites in Figure 3 appear rather differently. Two of the profiles, site 15 (TM104934) from Bunwell and site 35 (TF 832213) from Rougham, belong almost entirely to Cluster M8 (MD), the latter with a thin capping of Cluster M7 (CBC). The second profile from Bunwell, site 28 (TM122936), differs mainly in having a thick layer of Cluster M8 (CBC) at depth. In contrast to these, the profile at Tannington, site 43 (TM250692) is predominantly Cluster M7 (CBC) with an inclusion of Cluster M8 (MD) in the lower profile. The transect sections (Figs. 2B to 2D), show that using the M-cluster drift facies, the shallower profiles on middle and upper slopes are mainly Cluster M8 (MD) with some tendency for this to overlie Cluster M7 (CBC) in deeper boreholes.

For the deep profiles the major difference between the Measured Variable (M) and the Ratio/Magnetism Variable (R) classification is that while the former does not give a common stratigraphic pattern the latter does.

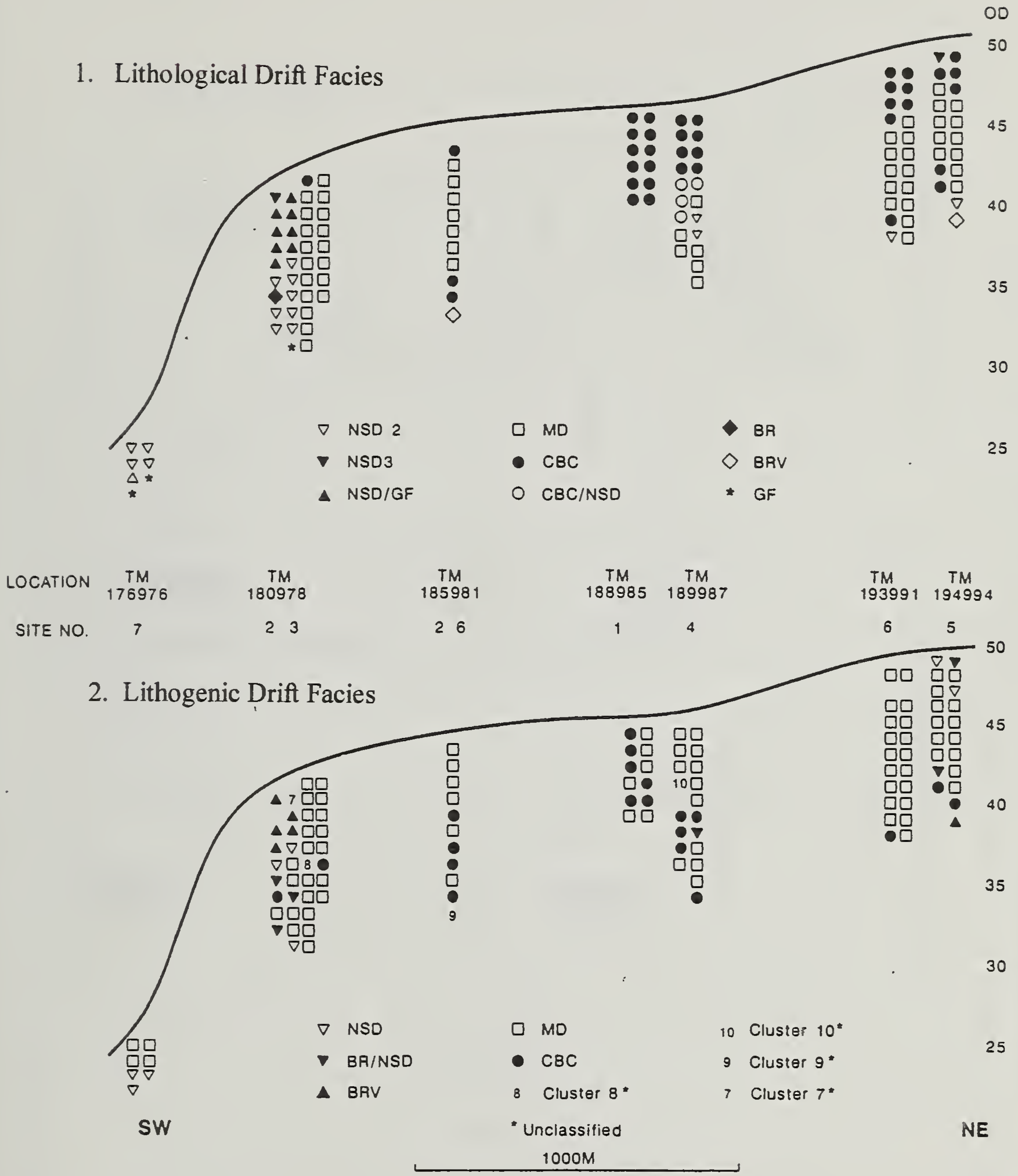


Fig. 2A. Vertical section of the transect at Flordon (see Fig. 1 for location). Upper section shows M cluster classification, lower section shows R cluster classification.

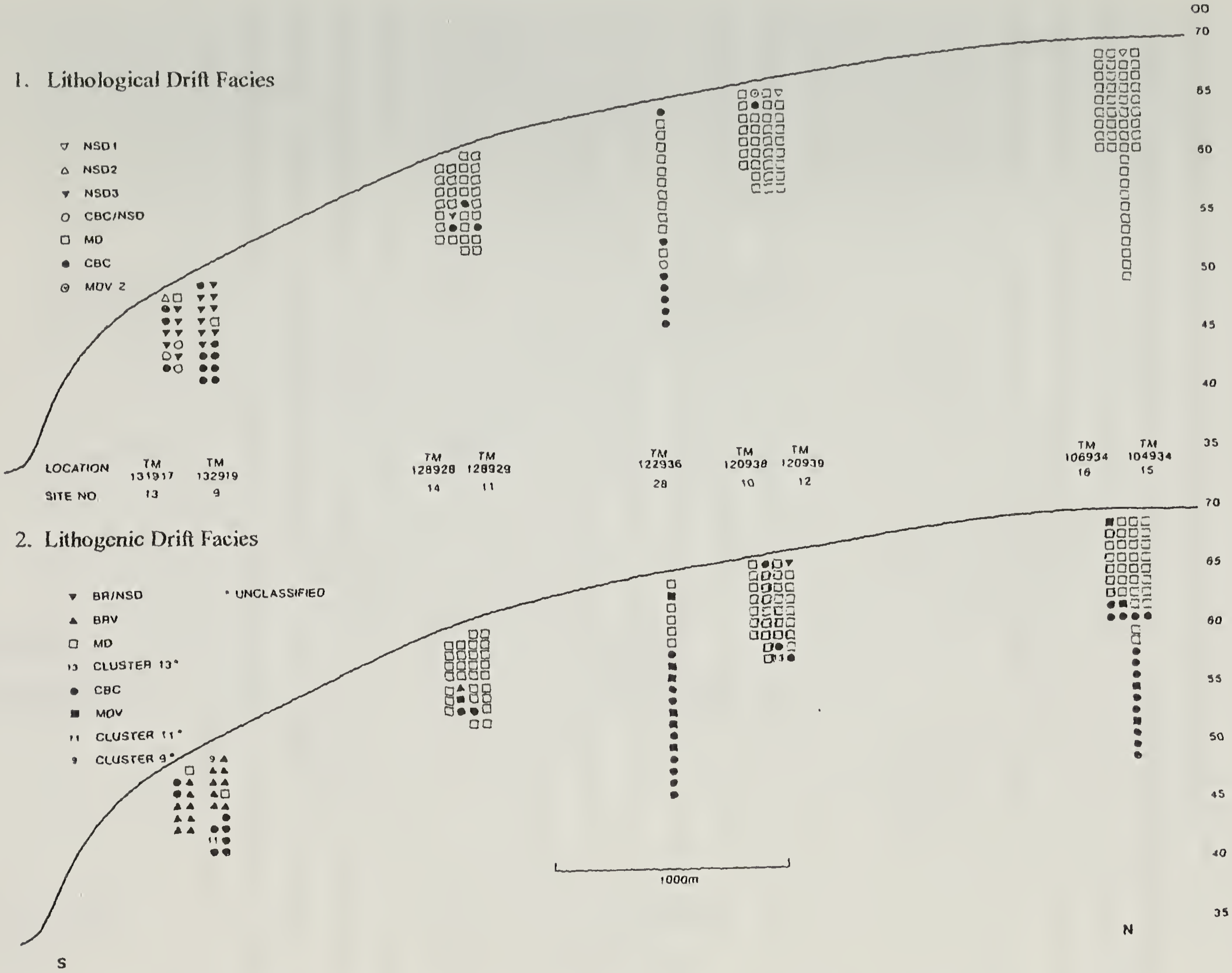


Fig. 2B. Vertical section of the transect at Bunwell (see Fig. 1 for location). Upper section shows M cluster classification, lower section shows R cluster classification.

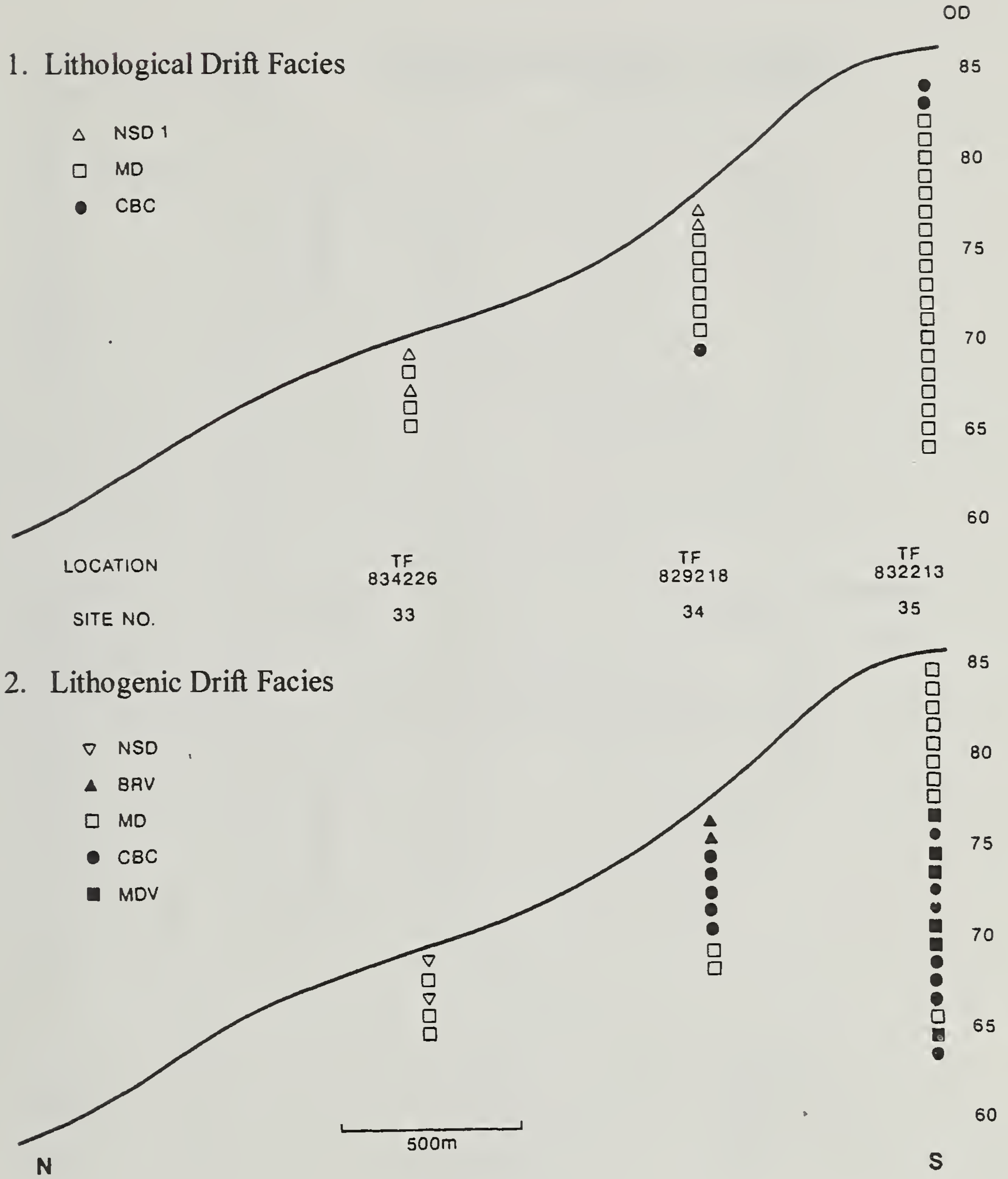


Fig. 2C. Vertical section of the transect at Rougham (see Fig. 1 for location). Upper section shows M cluster classification, lower section shows R cluster classification.

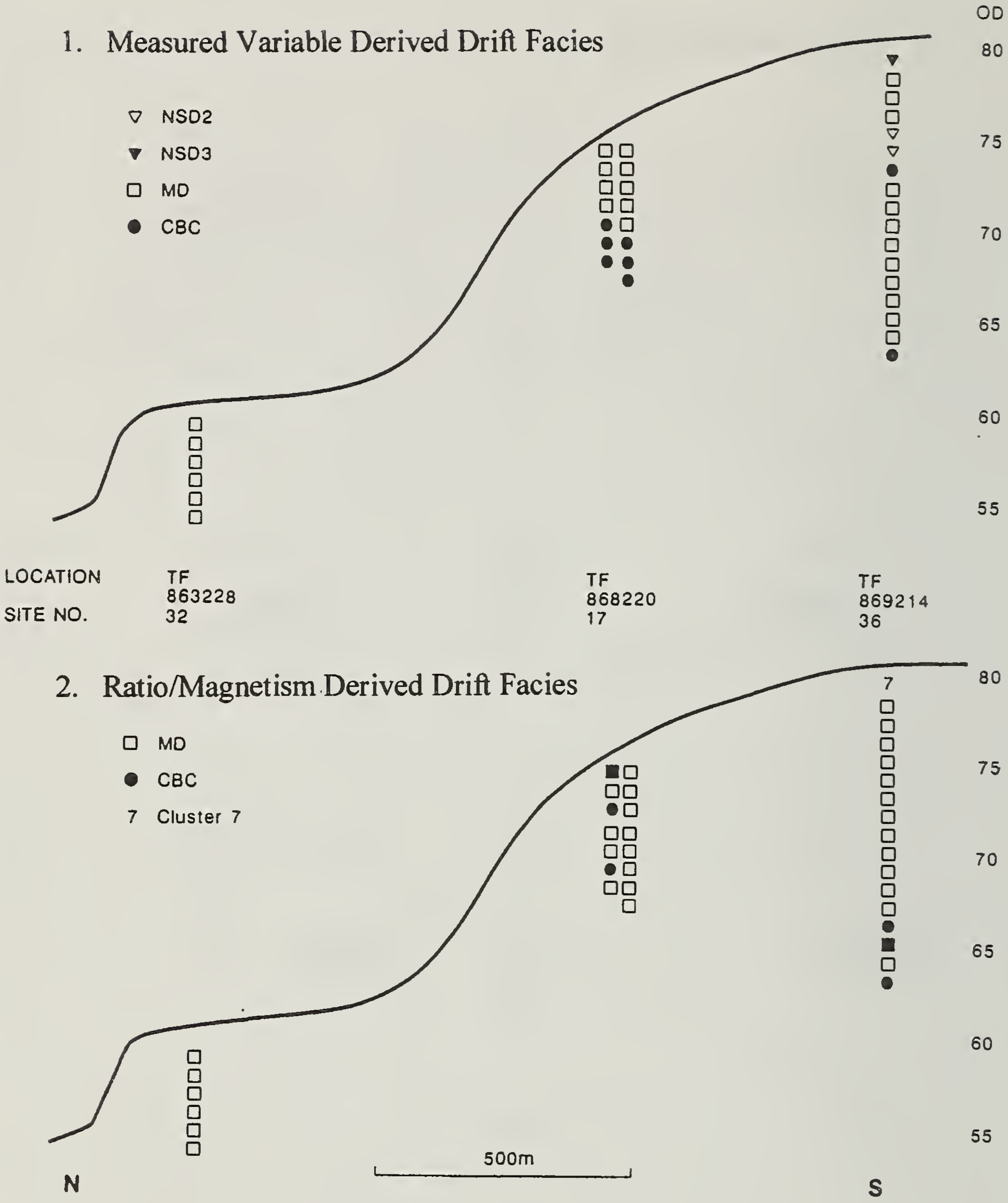


Fig. 2D. Vertical section of the transect at Weasenham (see Fig. 1 for location). Upper section shows M cluster classification, lower section shows R cluster classification.

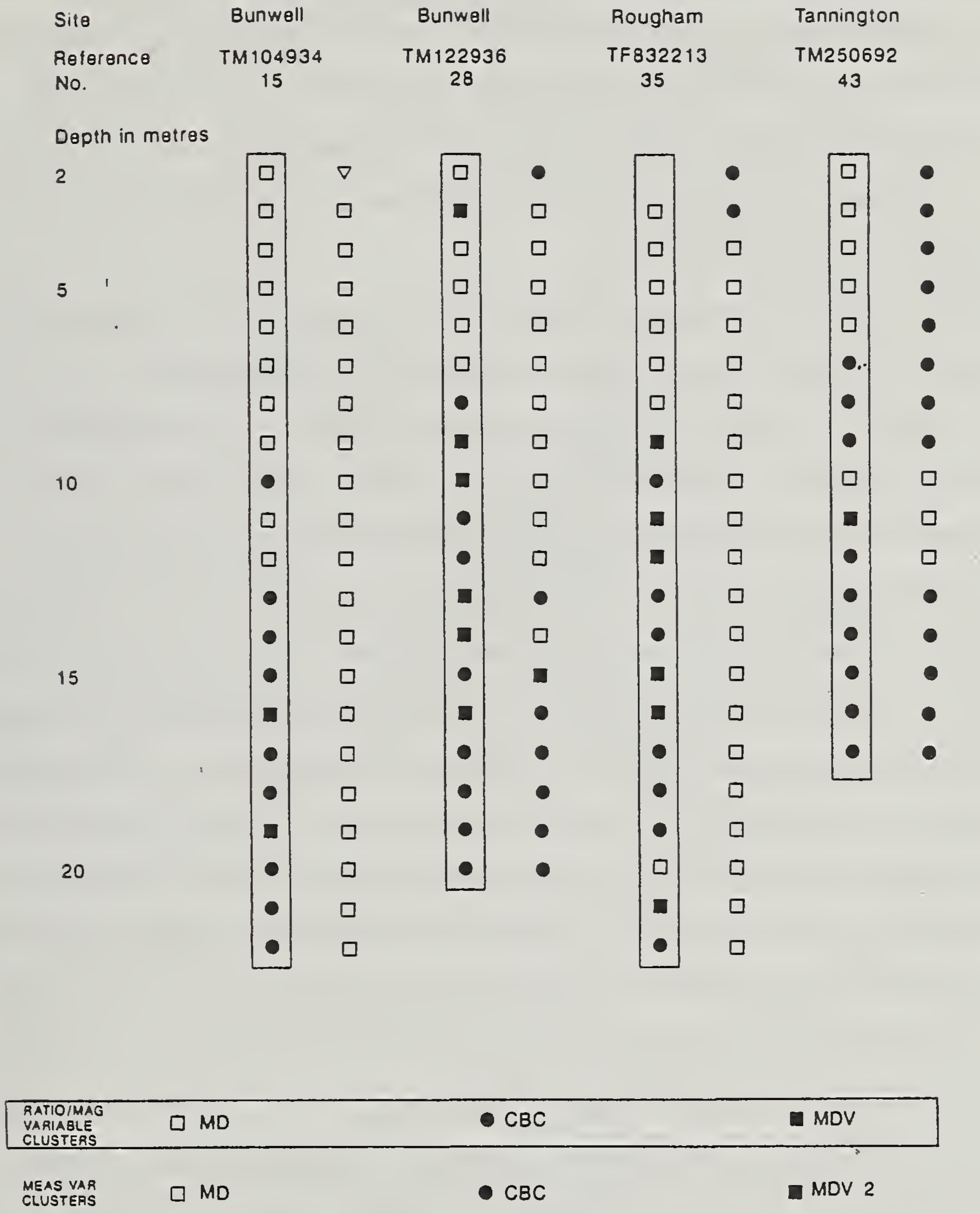


Fig. 3. Key stratigraphic profiles of the Lowestoft Till Group

The Flordon Transect (Fig. 2A) is different for both forms of drift facies classification. With M-derived facies, on the middle and upper slopes, there is at the surface, a varying thickness of Cluster M7 (CBC) which overlies mainly Cluster M8 (MD). Furthermore, there are indications throughout the transect that these drift facies lie on either Cluster M9 (Breckland variant - BRv) or Cluster M2 (Glaciofluvial - GF). With R variables there are no occurrences of Cluster R1 (MDv) and Cluster R6 (CBC) is at the surface in one of the profiles, at site 1 (TM188985).

While there are substantial differences in the stratigraphic picture provided by the two classifications, there is nevertheless a common thread. Everywhere except at Flordon, there is a tendency for chalkier tills (Marly Drift types of facies) to overlie less chalky tills (CBC facies) within the 'Lowestoft Till' group. At Flordon, this tendency is reversed when the M-cluster classification is used, but *maintained* if the R-clusters are employed.

Another important aspect of the local drift facies distributions is the relationships between the NSD and BR drifts and those of the 'Lowestoft Till' group. On the lower slopes of both the Flordon and Bunwell transects the two drift facies groupings are in juxtaposition and this is apparent using both M and R clusters for classification. At Flordon (Fig. 2A), between sites 2 (TM180978) and 3 (TM181979), there is a sharp, or fairly sharp, vertical boundary with MD (M and R) upslope and, for M-derived drift facies Cluster M5 (NSD/GF) over Cluster M1 (NSD 2) downslope. The R-derived downslope equivalents are Cluster R3 (BRv) and Cluster R5 (BR/NSD) with, in the latter, some Cluster R1 (MD) inclusions. At Bunwell (Fig. 2B), at sites 13 (TM131197) and 9 (TM132919), Cluster M7 (CBC) at depth is overlaid, at least in part, by Cluster M4 (NSD 3) and possibly by Cluster M10 (CBC/NSD). Using the R classification, CBC-type tills again appear at depth, overlain mainly by Cluster R3 (BRv). In addition, the transect sections in both east and west Norfolk, show on middle and upper slopes, some inclusions of BR and NSD drifts. These inclusions, as at site 4 (TM189987) Flordon, can be quite thick but they lack lateral continuity.

A further aspect of the local drift facies distribution concerns ‘surface drifts’ in the uppermost few metres on sites where, at greater depth, there are ‘Lowestoft Till’ group drift facies. This surface drift, for both forms of classification, is in the BR and NSD grouping.

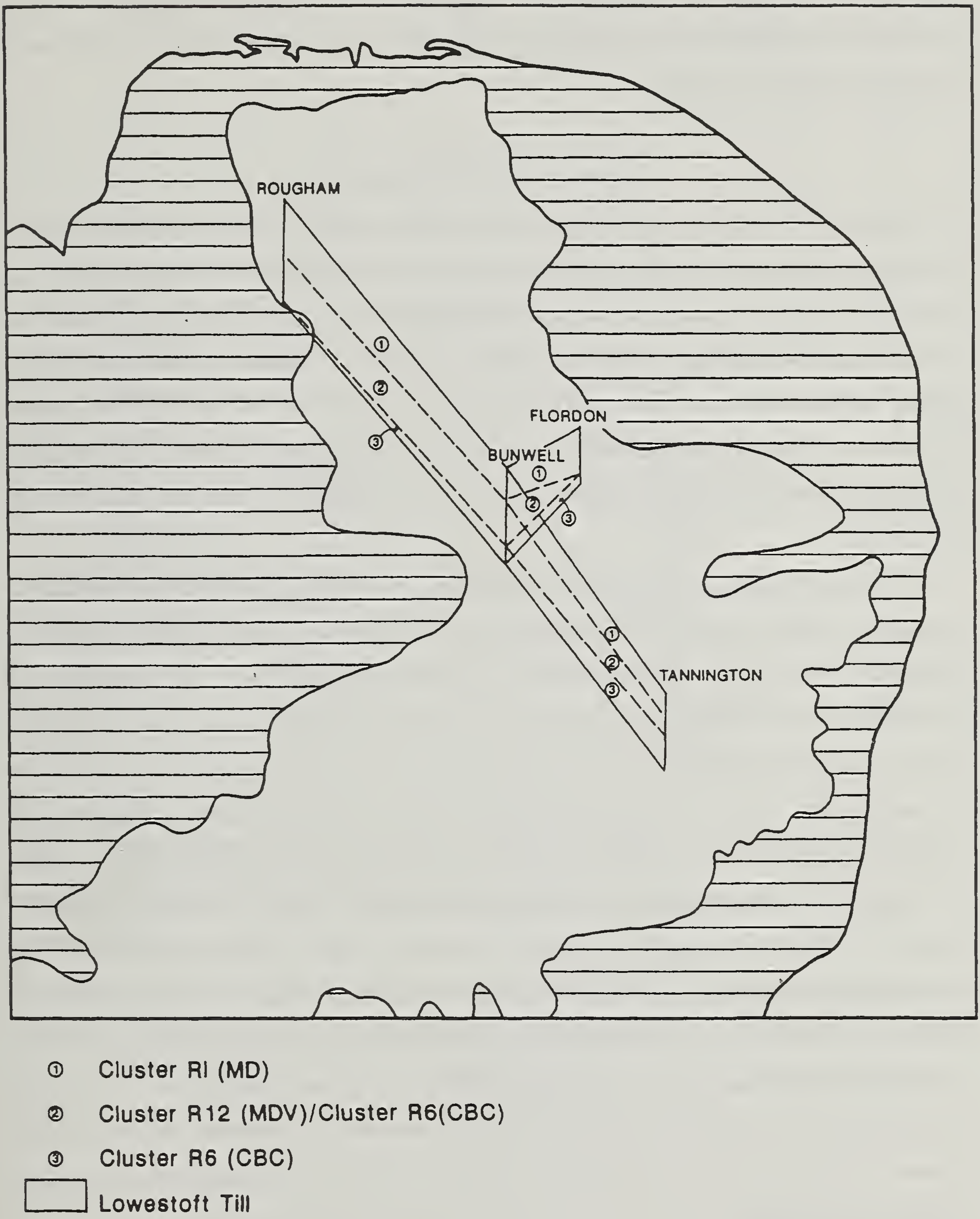


Fig. 4. Fence diagram showing the stratigraphic sequence in the Lowestoft Till Group across Norfolk and Suffolk.

At Flordon (Fig. 2A) this occurs at site 5 (TM194994), at Bunwell (Fig. 2B) at site 12 (TM120939), at Weasenham (Fig. 2D) at site 36 (TF869214) and at Rougham (Fig. 2C) at sites 33 and 34 (TF834226) and (TF829218) respectively. The occurrence tends to be more common on slopes than crests.

Regional Scale Distributions

Having dealt with drift facies distribution on local scales of up to several kilometres, on the east and west edges of the Chalky Boulderclay plateau in Norfolk, the spatial distributions of till facies throughout Norfolk and the more northern parts of Suffolk are now considered. The central plateau profiles are shown in Figure 5 and the classification of drift facies from samples collected during the Quaternary Research Association's (QRA) 1991 Field Meeting (Lewis et al. 1991; see sample details in Corbett 2001) are given in Table 1. The regional distribution of drift facies for M-derived units is shown in Figure 6A and for R-derived units in Figure 6B.

For the 'Lowestoft Till' group of R-derived drift facies on the central plateau, the Tannington profile, site 43 (TM250692), as one of the key sites with a three unit stratigraphy, has already been dealt with. The sites at Tibenham and Shipdham, 42 (TM129896) and 38 (TF971089) respectively, can be taken, like many of the shallower profiles on middle and upper slopes in the transects, to represent the upper part of the three unit stratigraphic sequence given by R-derived clusters. The QRA sites at Ingham, High Lodge and Tottenhill (Table 1) show, in the M classification, Cluster M8 (MD) over Cluster M7 (CBC). However, using the R-derived units the High Lodge near-surface sample is Cluster R12 (MDv). At Ingham, a sample taken from a scour channel which crosses the floor of the pit is classed as the intergrade Cluster M10 (CBC/NSD) or Cluster R1 (MD). At Beeches Pit (West Stow), upper and lower samples using the M classification belong to Cluster M8 (MD) but using the R classification the near surface sample in Pit 1 is part of Cluster R6 (CBC). The lower drift facies in Pit 2 is capped by beds which include in Pit 1 a calcareous tufaceous deposit considered interglacial and dated to oxygen isotope stage 11 (P. Rowe pers. comm.).

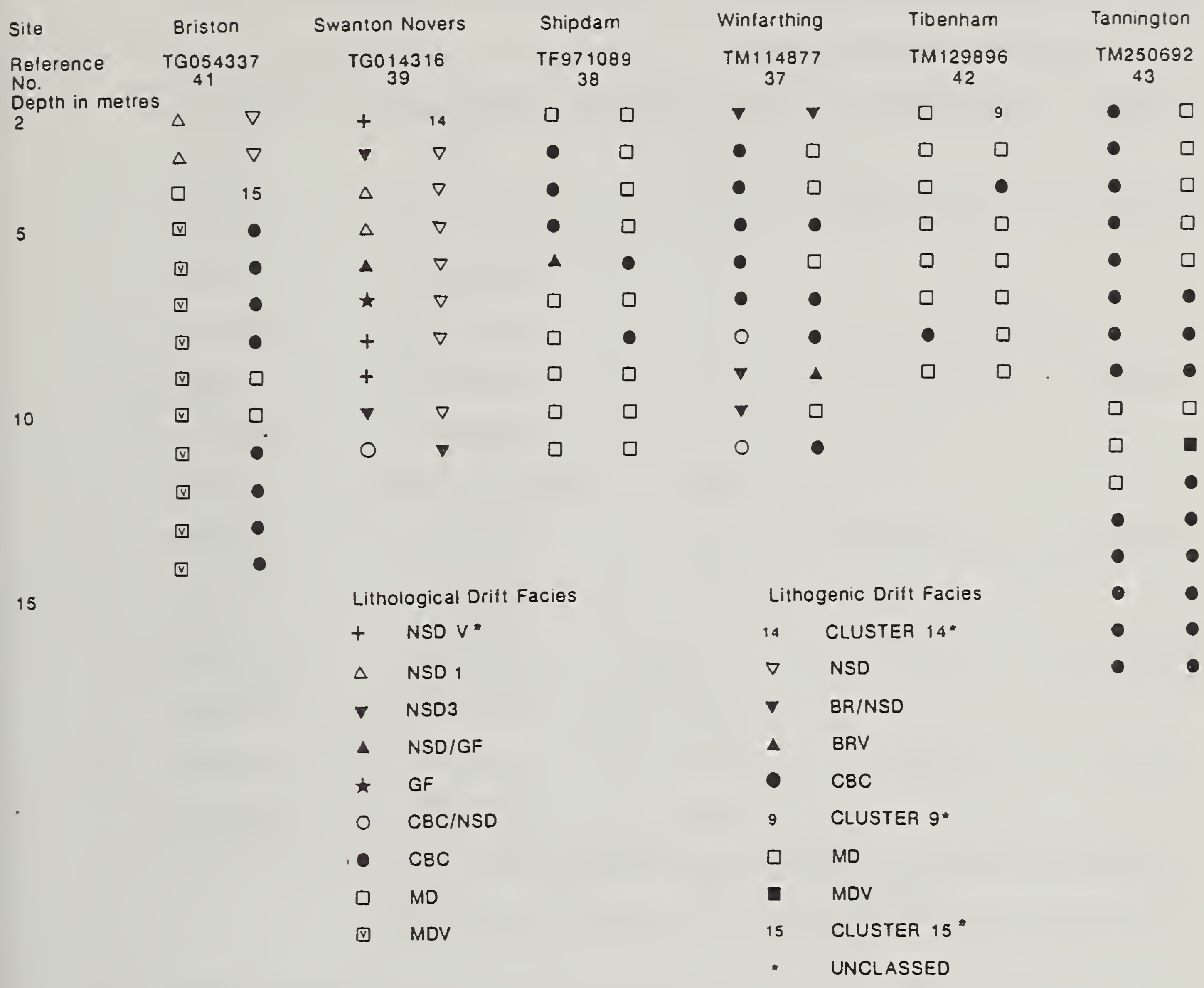


Fig. 5. Stratigraphic profiles from central Norfolk and Suffolk. At each site the left hand column shows M cluster classification while the left hand column shows R cluster classification.

Many of the sites referred to above, both above and below the chalk escarpment have Marly Drift over Chalky Boulderclay and this could be an abbreviated version of the three unit stratigraphic sequence referred to earlier. The West Stow site using the R classification is thus apparently exceptional.

In the far south of the study area, the reference site at Great Blakenham (see Corbett 2001) has, in the M classification, Cluster M7 (CBC) at the surface and at depth on both crest and slope sites. However, using R classification, the surface drift facies on slopes are

Table 1. Drift facies classifications for 1991 QRA excursion sites in west Suffolk and south and west Norfolk

Location	Grid Reference	Sample Depth (m)	Drift Facies (M)*	Drift Facies (R)**
Knettishall	TL 951798	3.0	M4 (NSD3)	R3 (BRv)
		3.0	M4 (NSD3)	R2 (NSD)
		4.5	M8 (MD)	R1 (MD)
Ingham	TL 855715	2.0	M8 (MD)	R1 (MD)
		2.5	M7 (CBC)	R6 (CBC)
		10	M10 (CBC/NSD)	R1 (MD)
West Stow	TL 798719	0.65	M8 (MD)	R6 (CBC)
		3.5	M8 (MD)	R1 (MD)
High Lodge	TL 739754	1.5	M8 (MD)	R12 (MDv)
		7.0	M7 (CBC)	R6 (CBC)
Tottenhill	TF 636115	17.0	M8 (MD)	R1 (MD)
		17.0	M7 (CBC)	R6 (CBC)

* data derived from Measured Variable Cluster Analysis (Corbett 2001)

** data derived from Ratio/Magnetism Cluster Analysis (Corbett 2001)

MD = Marly Drift; NSD3 = Third Cromer Till (North Sea Drift); CBC = Chalky Boulderclay; NSD = North Sea Drift; BRv = Breckland Drift variant; MDv = Marly Drift variant (see details in Corbett 2001).

Note: Samples listed above do not necessarily represent stratigraphic sequences

classed as either Cluster R1 (MD) or Cluster R10 (CBCv). This latter unit, which is also found in northeast Norfolk, has, in comparison with Cluster R6 (CBC) less total carbonate, (values around 40%), more non carbonate <63 μm fraction (about 40%), and twice its Median Destructive Field value (see Corbett 2001), which suggests some admixture with either NSD drifts or more likely with coversand. Finally at Briston, site 41 (TG054337), under a thin surface drift of Cluster M3 (NSD1) or alternatively Cluster R2 (NSD), the M-cluster classification gives a uniform profile of Cluster M15 (MDv), a unit characterised by

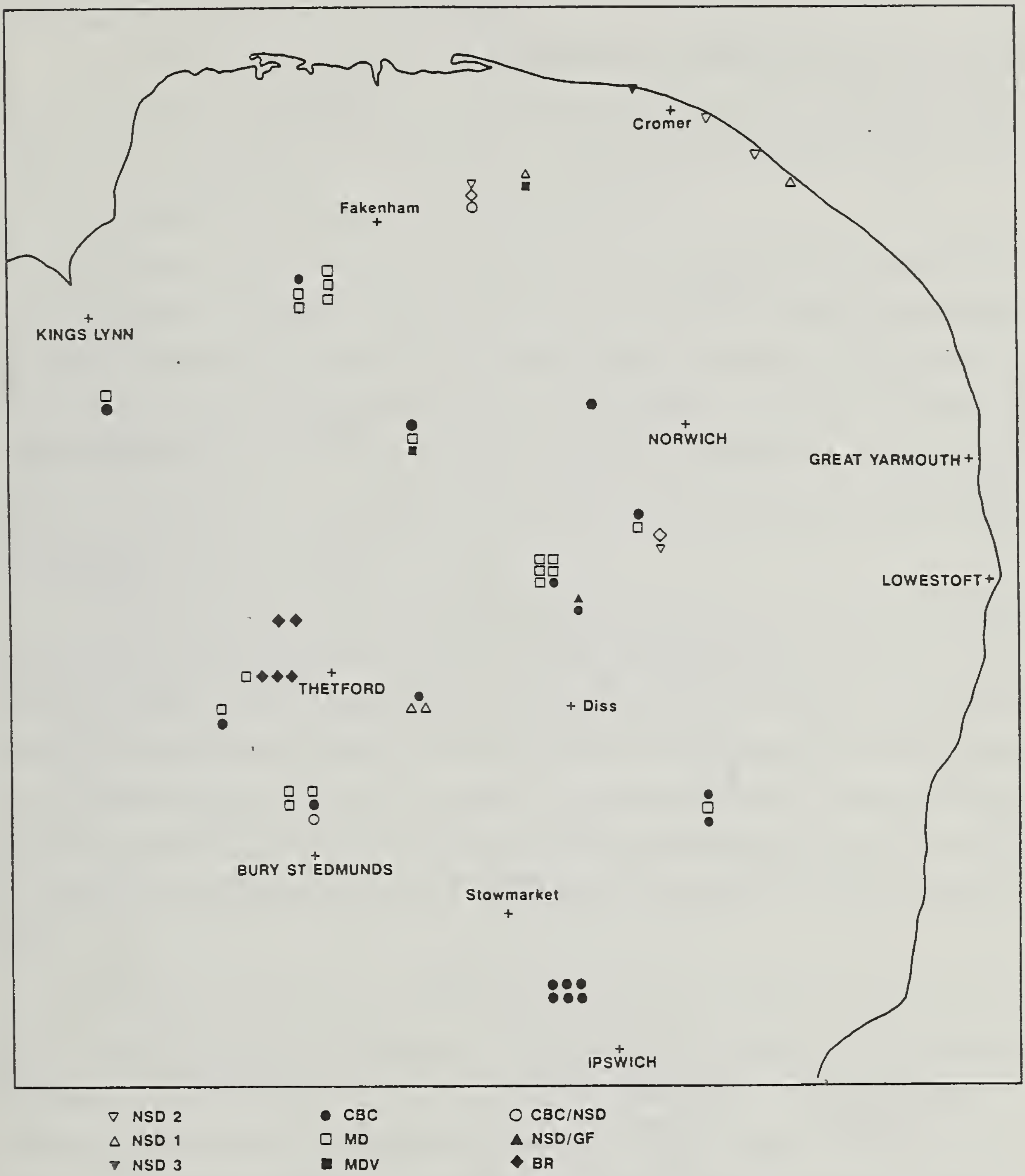


Fig. 6A. Regional scale pattern of M-derived drift facies. At individual sites, the vertical arrangement of drift facies symbols, are shown *down the page* while lateral change along transects and across sections is shown *across the page.*

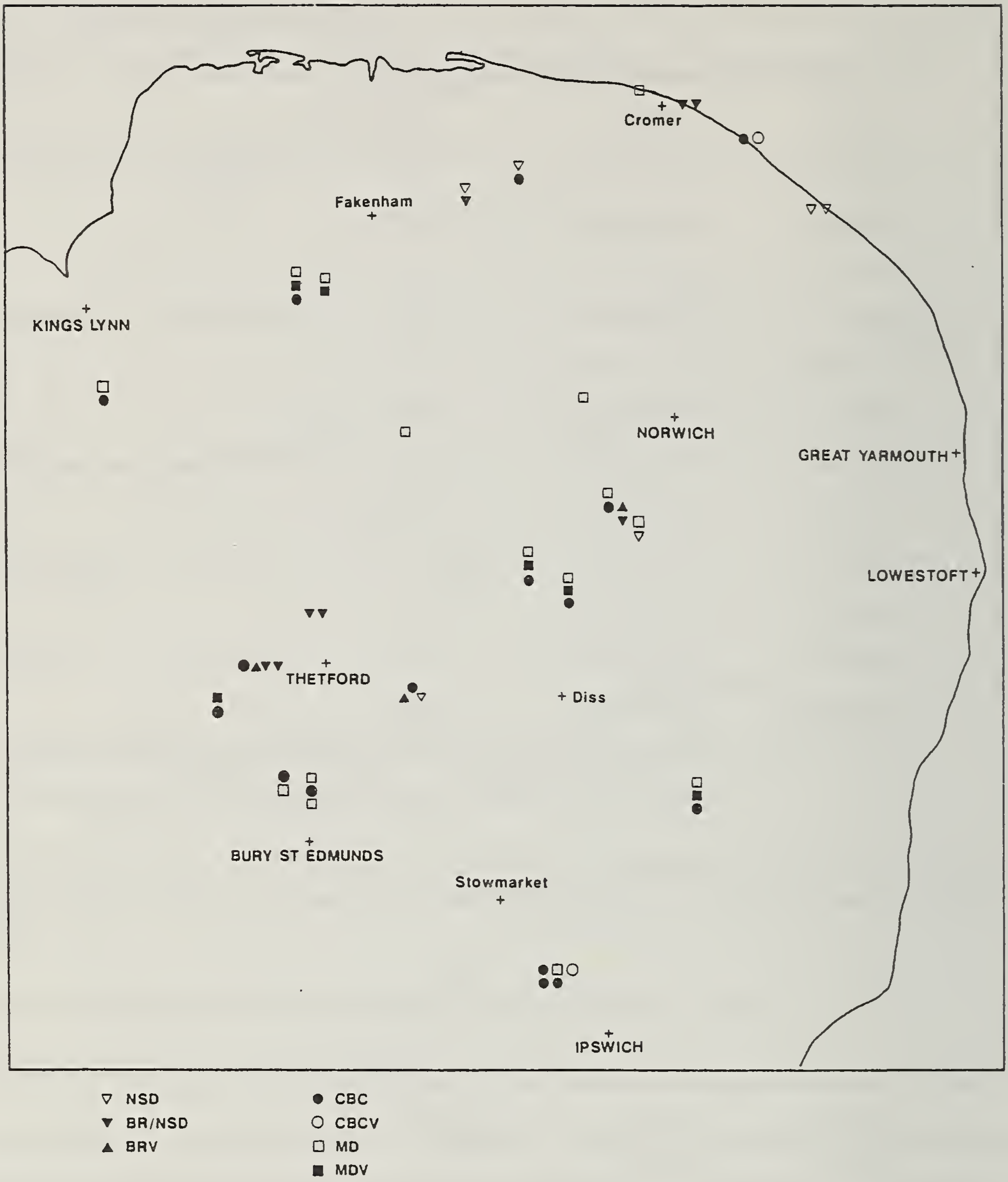


Fig. 6B. Regional scale pattern of R-derived drift facies. At individual sites, the vertical arrangement of drift facies symbols, are shown *down the page* while lateral change along transects and across sections is shown *across the page*.

its very high fine grained carbonate content. This drift facies occurs elsewhere only as a single occurrence in the mid-profile at Shipdham.

For the NSD and BR grouping of drift facies (Corbett 2001), their occurrence within the Chalky Boulderclay plateau, on lower slopes, as inclusions and as a thin discontinuous surface layer has been already described above. Such features can be seen in the profile on the central plateau at Winfarthing site 37 (TM114877).

Immediately outside the main spread of the Chalky Boulderclay plateau, near its northern periphery at Swanton Novers (TG014316; Fig. 5), the R classification gives a moderately deep profile of Cluster R2 (NSD) with Cluster R5 (BR/NSD) at the bottom. The M classification profile is more complex (Fig. 5) with Cluster M3 (NSD 1), Cluster M4 (NSD 3) and Cluster M2 (GF) over at depth, Cluster M10 (CBC/NSD). The presence of these North Sea Drift facies, on this thickness scale, so far west from their surface outcrops in north east Norfolk, is surprising.

To the west of the Chalky Boulderclay plateau in Breckland, the M classification (Fig. 6A) identifies all five plateau samples in a cluster unit which has in total only six cases - Cluster M6 (BR). The R classification (Fig. 6B), however, puts four of the five plateau samples into the intergrade Cluster R5 (BR/NSD) while the remaining one is used to name the unit Cluster R3 (BRv). Nearby at the QRA site at Knettishall, east of Thetford (Table 1), while the M classification puts the two samples from a brown sandy diamicton into Cluster M3 (NSD 1), the R classification makes one Cluster R2 (NSD) and the other Cluster R3 (BRv).

The taxonomic linkages in the R classification between the BR and NSD drifts recur in the reference samples from the north east Norfolk coast where both samples from Overstrand (Corbett 2001) are classed in Cluster R5 (BR/NSD). The R classification in north east Norfolk also makes a linkage between the two main groups of drift facies. The reference samples from Mundesley (Corbett 2001), being classed Cluster R6 (CBC) and Cluster R10 (CBCv), and those from West Runton, Cluster M4 (NSD 3) or Cluster R1 (MD).

CONCLUSIONS

For the drift facies derived from Cluster Analysis of M variables there is no obvious stratigraphic pattern even in the deeper boreholes. In contrast, some general points can be made regarding the vertical distribution - both on a local and regional scale - of the drift facies derived from R variables (Fig. 6B).

1. In the Chalky Boulderclay/Lowestoft Till group the drift facies equated with the Marly Drift occurs as a thick surface layer over most of the Chalky Boulderclay plateau in Norfolk and north Suffolk. It forms the upper unit of a three unit stratigraphic sequence, the lower one being equated with the Lowestoft Till *sensu stricto* (Baden-Powell 1948), the middle unit containing both Lowestoft Till and a Lowestoft Till facies of the Marly Drift. This finding is in agreement with that of Ehlers *et al.* (1987, 1991). However, the middle unit (Cluster R12 (MDv)) may be thin or absent to the east and south.

2. Although there is apparently, according to Cluster Analysis, a link between the drifts in Breckland and on the north east Norfolk coast, Cluster R5 (BR/NSD) and Cluster R3 (BRv) have not been found in northeast Norfolk.

3. Two of the reference sites in north east Norfolk have drift facies of the 'Lowestoft Till' group and one of these drift facies, Cluster R10 (CBCv) also distinguishes part of the surface drift on the slope at Great Blakenham in Suffolk.

4. At Knettishall, the deep infilled trough in the north east corner of the pit is by both classifications Marly Drift and this trough is cut into underlying drifts which include North Sea Drift facies. This arrangement concurs with the stratigraphic sequence at the Anglian stratotype (Corton Cliff, Lowestoft), where Lowestoft Till occurs stratigraphically above North Sea Drift. However, on inland sites other than Knettishall, there is no obvious order of depositional sequence for the Breckland- North Sea Drift grouping of drift facies.

ACKNOWLEDGEMENTS

I wish to thank the staff of the School of Environmental Sciences at the University of East Anglia for their support in this project. In particular I thank Alastair Grant for the computing statistics, Barbara Maher for proposing and supervising the work on magnetism and Tim Atkinson for his guidance on the presentation of results.

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BACK ISSUES OF THE BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK AND 50th JUBILEE VOLUME

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GEOPHYSICAL DEMARCATION OF THE SALINE INTRUSION AT CLEY-NEXT-THE-SEA, NORTH NORFOLK

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ABSTRACT

The position of the saltwater intrusion into the coastal chalk aquifer at Cley-next-the-Sea, north Norfolk, UK, is established using the Transient Electro-Magnetic method. The geoelectric sections derived permit construction of a simple conceptual model in which six distinct hydrogeological units are recognised. These are the intrusion itself; fresh, brackish and highly saline groundwater zones; confining Holocene deposits and a freshwater lens in Blakeney Eye. The intrusion, which is no deeper than 50 metres below sea level within 1600 m of the coast, is affected by pumping from an inland borehole.

INTRODUCTION

Saline intrusion

Saline intrusion is the phenomenon of saline waters entering fresh groundwater systems and is commonly encountered in coastal aquifers. As a chloride concentration greater than 300 mg l^{-1} is sufficient to classify a groundwater as saline (Owen *et al.*, 1991), it takes little seawater (at 19g chloride l^{-1}) to pollute an aquifer (McDonald *et al.*, 1998). This is potentially a serious problem, particularly where freshwater supplies are limited. Incidents of saline intrusion occur worldwide and are extensively documented (Salt Water Intrusion Meeting (SWIM) papers 1968 onward).

To protect coastal groundwater resources it is necessary to understand what causes, and what controls, saline intrusion. Early studies on the position of the saltwater/freshwater interface in coastal aquifers (DuCommun 1828; Fetter 1994; Ghyben 1888, and Herzberg, 1901) showed that the depth to the top of a saltwater wedge, intruding from the bottom of an

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aquifer, is approximately forty times the height of the water table above sea-level. This is known as the Ghyben-Herzberg relation and is derived from density considerations. Over the past century, theoretical models describing this relationship have been refined to account for assumptions made in the original studies. In addition, Hubbert (1940), Todd (1953), Cooper (1959) and Glover (1964) have all contributed to our understanding of subsurface saltwater/freshwater interactions.

More recently, research into saline intrusion has typically concentrated on mapping and monitoring for the purposes of groundwater resource protection (Yuhr & Benson 1992; Melloul & Goldenberg 1997). In this study, assessment of the position of the interface at Cley-next-the-Sea should help to delineate the dynamic behaviour of groundwater flow and direct resource management. This knowledge will aid our understanding of hydrogeological interactions between what are essentially a potable water resource and a contaminant.

Local and regional occurrences

Wiveton Marsh, immediately west of Cley-next-the-Sea (forthwith 'Cley') rests near the foot of Blakeney Spit, on the north Norfolk coast (Fig. 1). As the spit is a feature of significant coastal geomorphological importance, work in the area has typically concentrated on the Quaternary geology (Funnell and Pearson, 1989; Andrews *et al.*, 2000; Funnell *et al.* 2000). These studies identified a number of Holocene and pre-Holocene deposits at Cley. While the nature of these deposits exerts some control on the saline intrusion, the intrusion itself was not examined. However, saline intrusion of groundwater at Cley was studied by Thomas (1992) and at also at Morston (to the west) by Burren (1998). Hiscock *et al.* (1996) noted salinity at various depths within the chalk throughout Norfolk, but record it (for the most part) as evidence of old marine waters.

Other East Anglian studies have concentrated on the Pleistocene Crag aquifer (a shelly, marine sand with silt and clay facies) to the east (Erskine, 1991; Holman, 1994; Holman and Hiscock, 1998; Holman *et al.*, 1999). Erskine (1991) established the degree to which tidal fluctuations affect water levels in the Crag, concluding that waveforms are effectively dampened within 400m of the coast. The degree of mixing occurring at the saltwater/freshwater interface responds to such fluctuations, which consequently dictate water quality. Holman and Hiscock (1998) found that, in the Thurne catchment, drainage of the overlying materials (alluvium, peats, loess and glacial drift) for agricultural purposes,

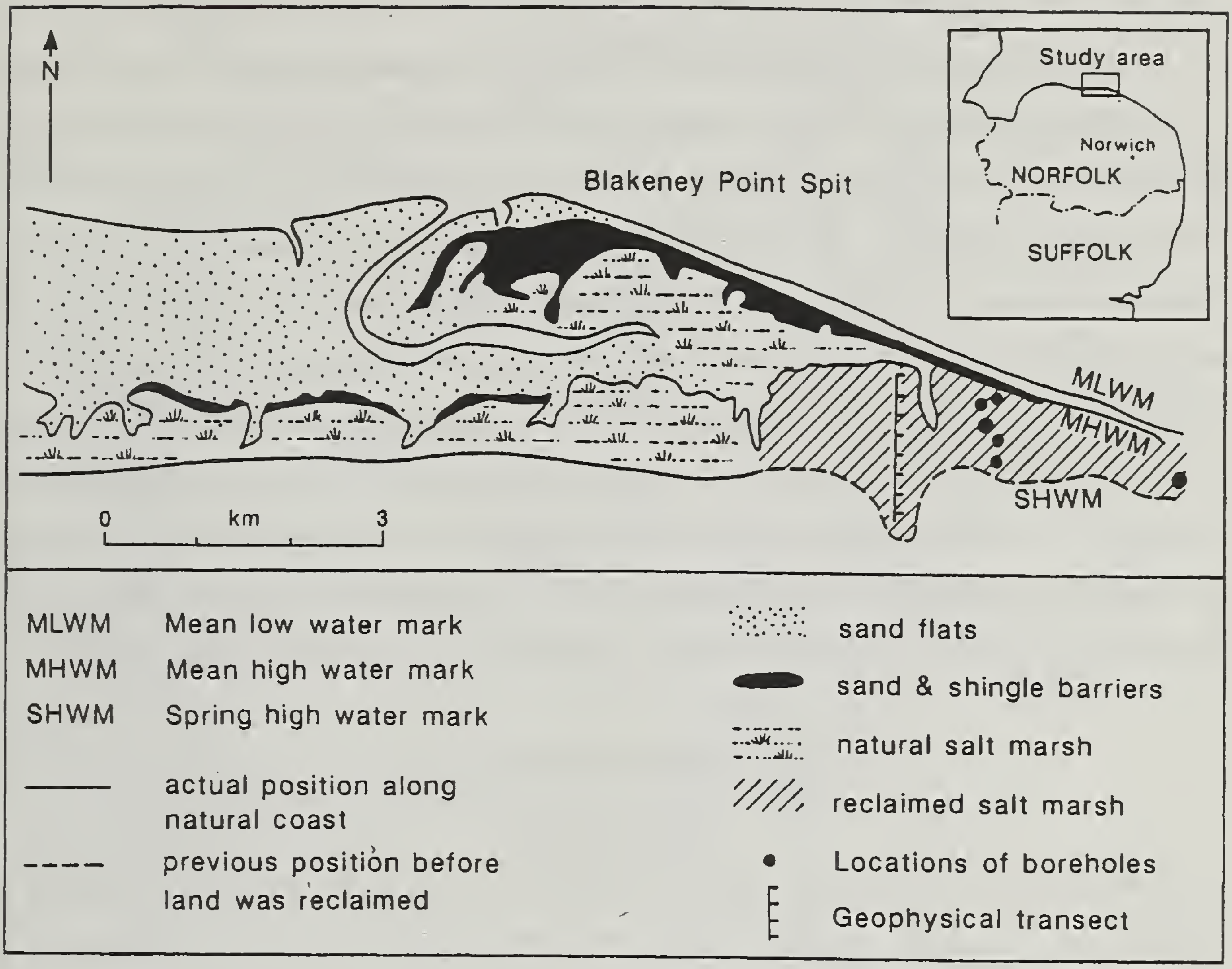


Fig. 1. Location of study site and surface geology (after Andrews *et al.*, 2000).

reverses the hydraulic gradient between the land and the sea. Thus, aided by the presence of a barrier beach and impermeable surficial Holocene deposits, saltwater is drawn into the aquifer beneath sea level and, where the drainage network significantly penetrates the alluvium etc., into the surface waters. Surface salinity has been the subject of research from the beginning of the century (Pallis, 1911) and, with the development of Sizewell nuclear power station, possibly accounts for the greater interest in intrusion into the Crag than the Chalk.

Geophysics and saline intrusion

As saline water is highly conductive, electrical and electromagnetic geophysical techniques are valuable tools for its identification. Such identification usually utilises borehole logging or d.c. resistivity (vertical electrical sounding (VES)) techniques (e.g. Monkhouse and Fleet, 1975; Lebbe & Pede, 1986). By comparison (to d.c. resistivity), the Transient (or Time-Domain) Electro-Magnetic method (TEM/TDEM) exhibits less susceptibility to lateral variations (because of smaller arrays for equivalent or greater depth penetration), improved resolution and a reduction in interpretative ambiguity. However, to date, no work has been published on the use of TEM for the identification of saline intrusion in the UK. Although some hydrogeological TEM projects have been undertaken by UK workers (Al-Khabouri, 1997; Meju *et al.*, 1996), most precedents in its application to saline intrusion are from Israel (Goldman *et al.*, 1988,1991 & 1996; Melloul and Goldenberg 1997), and the United States (Fitterman 1986; Mills *et al.*, 1988; Hoekstra & Blohm, 1990; Yuhr & Benson, 1992).

DESCRIPTION OF THE AREA

Physiography

The physiography of the area is shown in Figure 2. The elevated land to the south of Wiveton Marsh attains a height of some +35m OD. It dips to the north at an angle of approximately 4° until reaching the drained salt marshes at sea level. The marshes are bounded by an artificial sea wall, which attains elevations between +3 and +5 m OD, to the north, east and west. Other important features include Blakeney Eye (see below) in the northern part of the marsh (also attaining an elevation of between +3 and +5 m OD), the north flowing River Glaven to the east, which bends westward after passing the 'Eye' (separating it from the Spit) and the New Cut (a drain) in the west. To the west and north-west the fresh marshes are bordered by intertidal muds and salt marshes (Funnell and Pearson, 1989). The extensive drainage network lacing the surface of Wiverton marsh is not depicted in Figure 2.

Geology

The modern surface sedimentary environment (Andrews *et al.*, 2000), is composed predominantly of coarse barrier sediments and fine back barrier sediments (Fig. 1). The

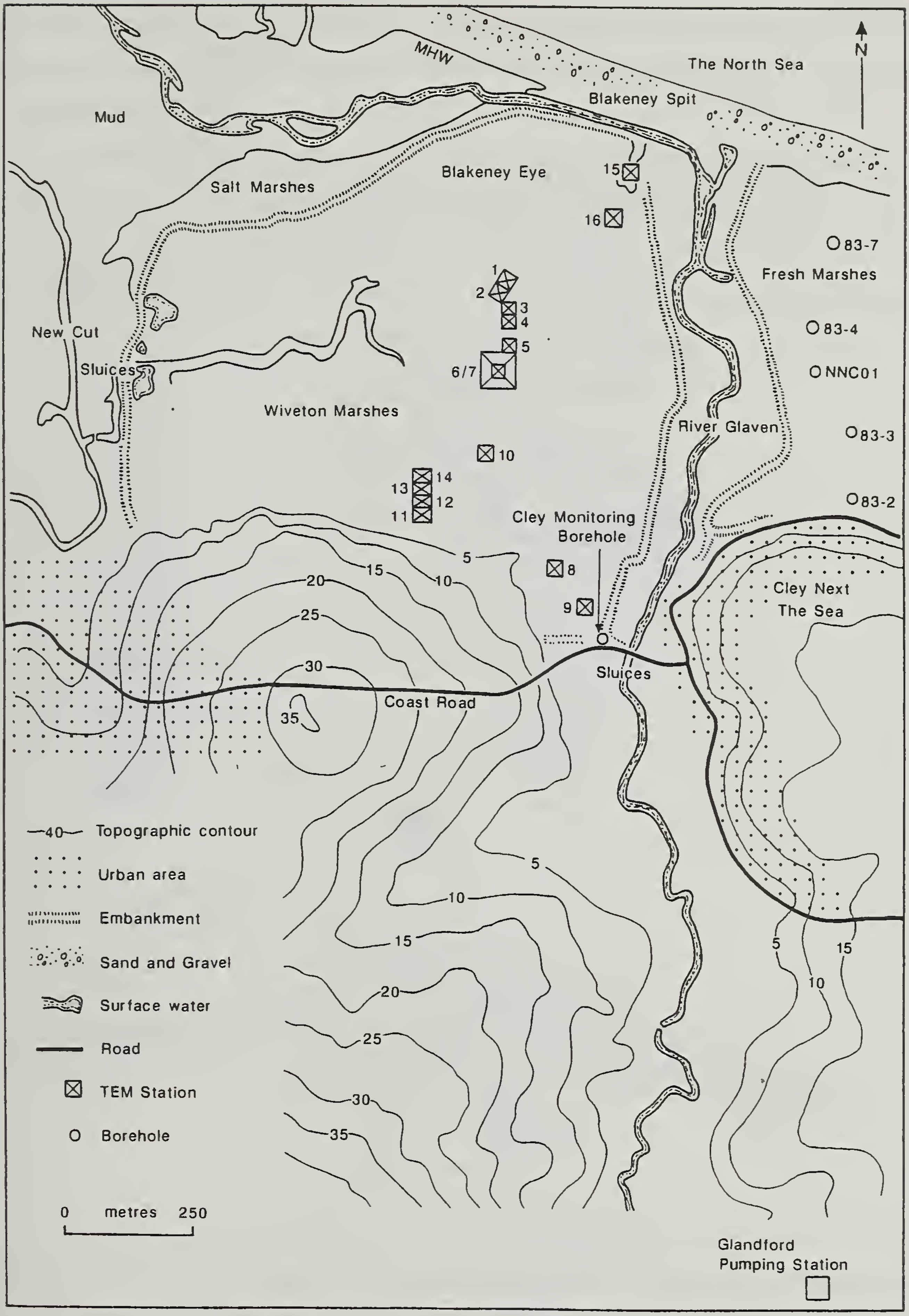


Fig. 2. Map illustrating main features of study site including TEM stations and borehole locations.

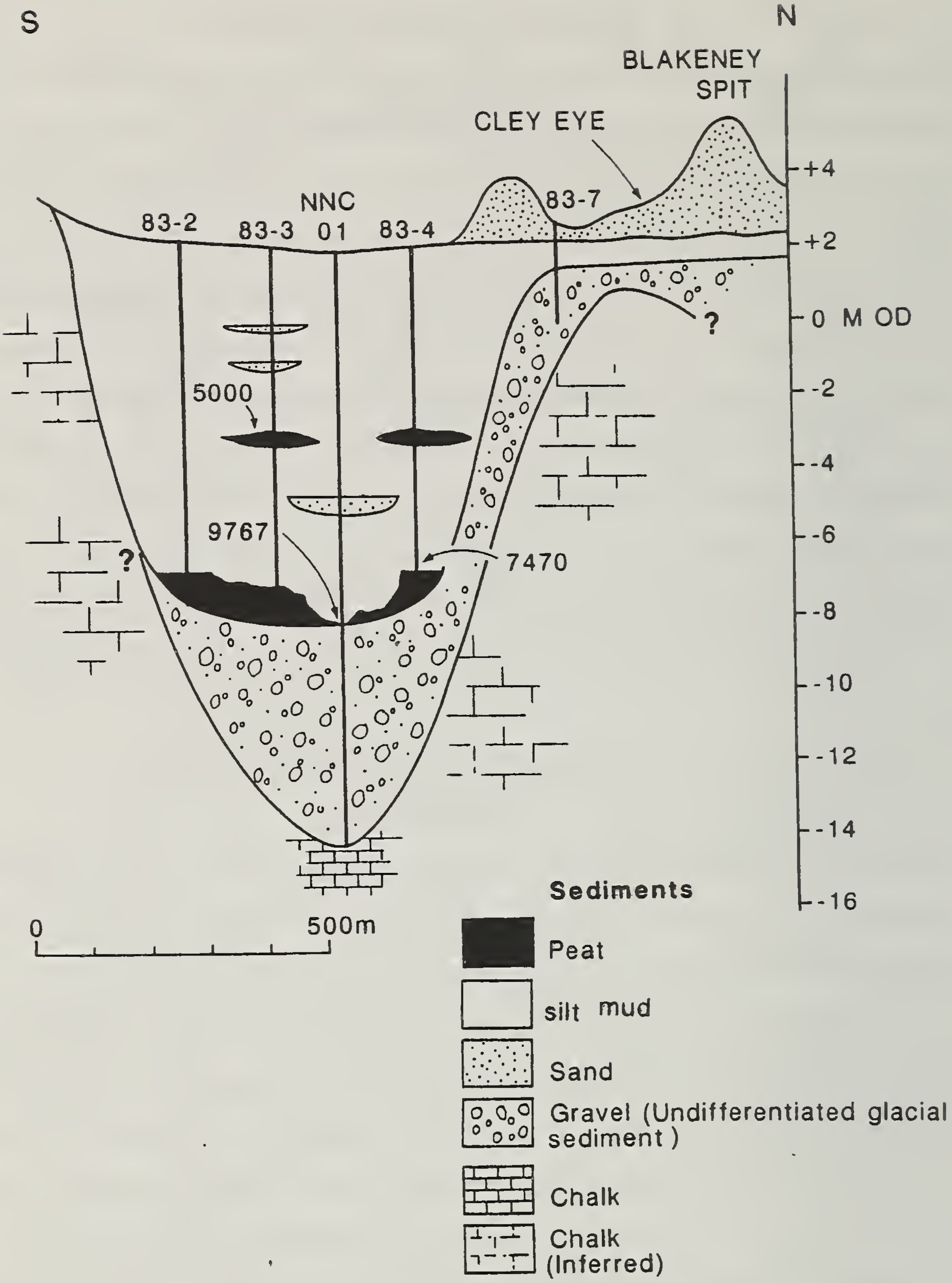


Fig. 3. Geological transect at Cley (after Andrews *et al.*, 2000) based on borehole and power auger information. 83-x numbers from Funnell and Pearson (1989). The depth to the top of the Chalk is based on seismic data from Chroston *et al.* (1999). The landward margin is drawn to the +3m OD contour. Radiocarbon dates are in calibrated years BP.

underlying Holocene deposits extend to a maximum depth of approximately -12.5mOD and directly overly either the Cretaceous Chalk or late Pleistocene glacial sands and gravels (Andrews *et al.*, 2000; Fig. 3).

The Pleistocene geology forms a ridge trending WNW-ESE beneath the eastern half of Blakeney Spit, with a shallow, parallel trough to the south (Fig. 4). This is believed to correspond with a trough in the Chalk, noted to extend to depths of at least -14m OD (Chroston *et al.*, 1999; Andrews *et al.,* 2000). At points, the glacial ridge emerges above the

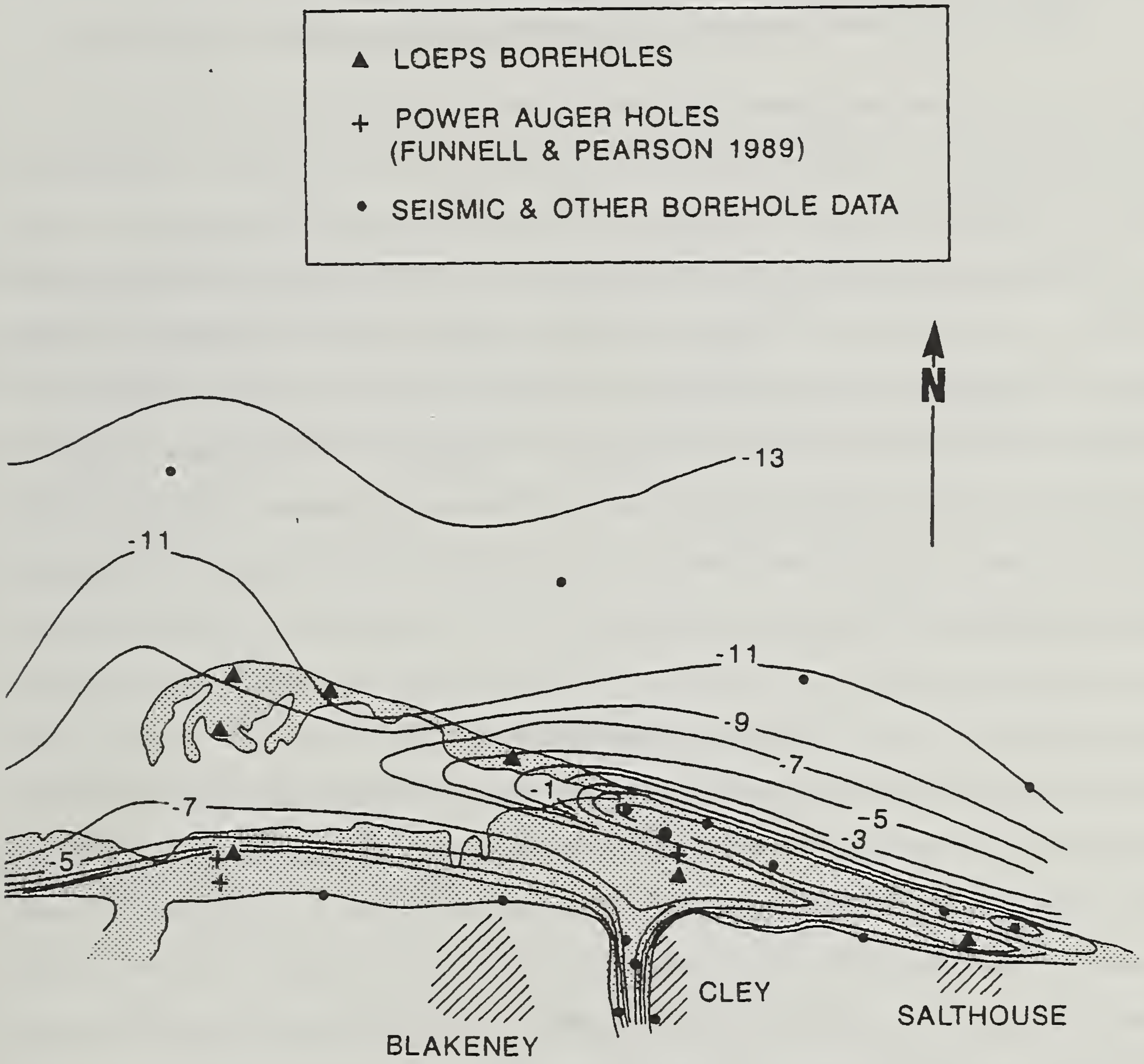

▲ LOEPS BOREHOLES
+ POWER AUGER HOLES (FUNNELL & PEARSON 1989)
• SEISMIC & OTHER BOREHOLE DATA
N
-13
-11
-11
-9
-7
-1
-5
-3
-7
-5
CLEY
SALTHOUSE
BLAKENEY

Fig. 4. Contour map of the pre-Holocene surface in the Cley area relative to Ordnance Datum based on borehole, auger and geophysical evidence after Andrews *et al.* (2000). Dots mark position of borehole or geophysical spot data. The +3m landward contour is taken as the depositional edge of the Holocene deposits. Shaded area represents morphology of the modern coastal zone.

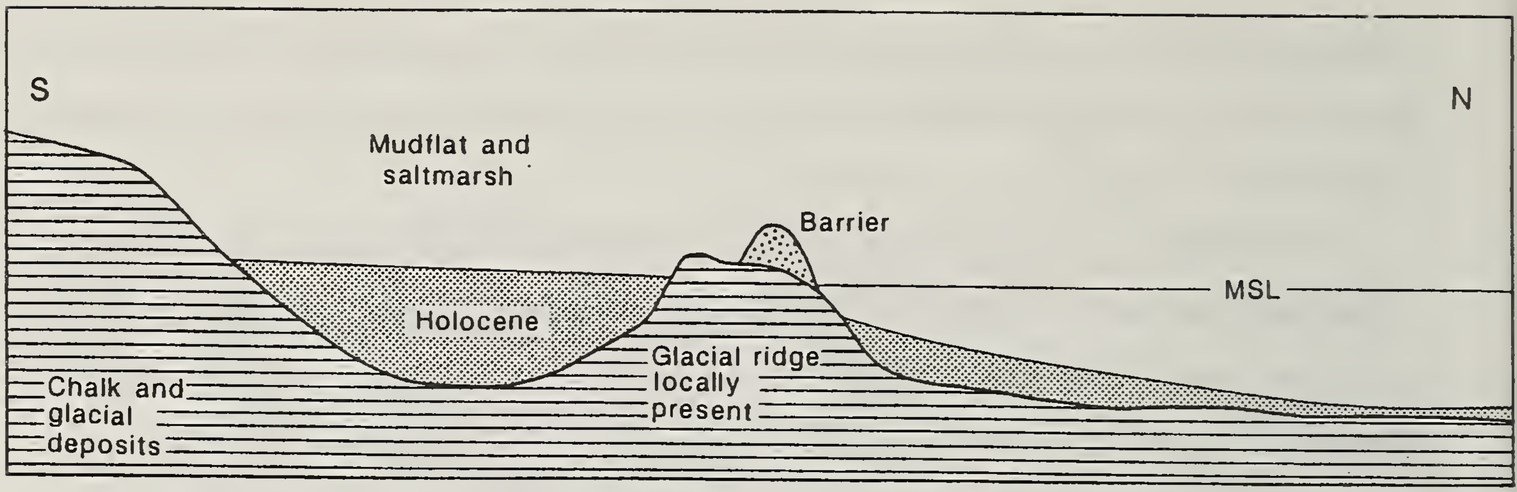


Fig. 5. Schematic geological cross section across the coastal zone at Cley.

Holocene sediments in small hills or 'Eyes' (e.g. Blakeney Eye, see Fig. 2). A typical cross section through Blakeney Spit and the associated marshes is given in Figure 5.

The Quaternary geology overlies the 'Basal mucronata Chalk' of the Belemnitella Mucronata zone (Peake and Hancock 1961), a firm, white, fine-grained limestone. Considered as a single unit, the Chalk may be several hundred metres thick. The general dip of the strata here is 1° ENE, but locally it forms an apparent northward facing shallow cliff at the southern margin of the Holocene deposits (Funnell & Pearson, 1984). This cliff is overlain by glacial deposits (the 'Blakeney gravels'). The upper 45m of the Chalk form an effective aquifer (see below).

Hydrogeology and hydrology

The Holocene back barrier sediments forming the marsh are composed of clay and fine silts. These deposits are intercalated with occasional layers of peat and sand (Funnell and Pearson, 1989; Andrews *et al.*, 2000), which increase the overall hydraulic conductivity. However, the marsh deposits are predominantly clay and thus act as an aquitard. The coarse barrier sediments, composed of sand, gravel and shingle, are considerably more permeable, as are the Pleistocene gravels underlying the Holocene. Typical hydraulic conductivity values for clay and well sorted gravel are, respectively, 10^{-6}-10^{-3} and 10-10^{3} m d^{-1} (Fetter, 1994).

The Cretaceous Chalk has a primary porosity of 30-50% and a hydraulic conductivity of 10^{-4}-10^{-3} m day^{-1} (Price *et al.*, 1976). The abundance of fractures in the top 50-60 m results in significant increases in the latter figure. Using an accepted figure for aquifer thickness of 45 m at Cley (Environment Agency, 1999) and a transmissivity of 4405

$m^2\ d^{-1}$ (Anglian Water, 1994), bulk hydraulic conductivity is calculated to be approximately 98 $m\ d^{-1}$. This figure is high, but the figures are derived from a pumping test (at Glandford pumping station, ≈3 km south of Wiveton Marshes) undertaken in the Glaven river valley), where dissolution features are likely to be enhanced (Price, 1987). The same pumping test produced a storativity value of 0.05. For caveats regarding these figures see Foley (1999).

The hydraulic gradient is approximately 0.0009, based upon the chalk water level in the Cley monitoring borehole (1.45 mOD; see Fig. 2) and the borehole's distance from the sea (1600m). From the above, the volume of freshwater discharging beneath the marshes is estimated to be ≈ 4 $m^3\ d^{-1}$ per metre of coastline.

The chemistry of the water sourcing the Cley monitoring borehole is of type Ib (after Hiscock, 1993; Hiscock *et al.*, 1996). Type Ib is an unconfined chalk groundwater of modern composition, although lacking NO_3. Thomas (1992) and Hiscock *et al.*, (1996) found the chalk groundwater to mix with modern seawater at the base of the borehole, which has been monitored for saline intrusion since at least 1990.

Wiveton Marsh has been drained for several centuries, principally for pasture. Funnell and Pearson (1984) recognised 14 different sedimentary environments on the north Norfolk coast, but stated that reclaimed land consists of embanked and drained upper saltmarsh. The marsh is currently drained into the New Cut to the west via a culvert beneath the embankment. Freshwater enters the marshes through springs and seepage discharging at the foot of the higher ground to the south (Fig. 2). At least one of these springs discharges directly into the drainage network. The marshes are subject to periodic inundation by the sea, with the last occurrence in 1996.

METHODS

Survey design

Two complementary geophysical surveys, using TEM and VES, were undertaken along a c.1500 m north/south transect across Wiveton Marshes (Fig. 2). These were supplemented by a geophysical borehole log of the Cley monitoring borehole. Sixteen TEM stations were located along the transect according to the presence of cattle and ditches. The objective was to map the depth to the intrusion as it changed from the coast landward and to tie the results of the TEM survey to the available control boreholes. Each station was oriented E–W (where possible) and located to an (estimated) accuracy of ± 1 m using tapes and compass bearings.

The decision to use TEM was based partly on its recognised value for detecting saline intrusion (Goldman *et al.*, 1988; Melloul and Goldenberg, 1997) and partly on the depth of penetration required: the intrusion was known to be approximately 42m below datum (Thomas, 1992). The device used for the TEM soundings was the Geonics Protem 47.

The Transient/Time Domain Electro-Magnetic (TEM/TDEM) method

The following description has been adapted from Fitterman and Stewart (1986), the Geonics Ltd. Protem 47 operating manual (1994) and Reynolds (1997):

In the use of TEM, a transmitter passes a constant, direct current through a large loop of cable laid on the ground. This current creates a primary magnetic field. An electromotive force is induced in a conductor when the magnetic field surrounding it changes. Thus, when the transmitter current is switched off, the primary field is interrupted, and currents are immediately induced in the ground (a conductor) that maintain the primary field. The induced primary field lasts only so long as it takes for the current to dissipate from the transmitter loop. Following this period the induced currents, which rapidly diffuse into the ground and decay, develop their own (secondary) magnetic fields. After a short interval, the strength of the induced currents becomes proportional to both the resistivity of the ground and time. The changing secondary magnetic fields, associated with the decaying currents, themselves induce a current in a receiver coil at the surface. This current (the 'Transient') also decays, but whilst doing so is measured (in volts) at the receiver at discrete intervals. Formation resistivity data is obtained due to the proportionality between induced current strength and ground resistivity. Because the currents induced in the earth have a maximum strength at some particular point (the locus), which gets deeper below ground with time, the voltage measured at the receiver coil over time corresponds to progressively greater depths.

Depth of penetration is related to the size of the loop, the amplitude and frequency of the induced magnetic field and the resistivity of the ground. Because of these factors, no absolute figure can be given regarding maximum and minimum depth penetration. Qualitatively, however, maximum depth penetration is typically 2.5 times loop edge length

(40m in this survey), although less penetration is achievable in a conductive medium where extensive current diffusion may occur near the surface.

The benefits of using TEM, as opposed to d.c. resistivity methods, include a small area over which data integration occurs. Because the station surface area is small relative to depth, readings are less susceptible to heterogeneities in the Earth, thereby satisfying the later modelling assumption that layers are homogeneous. Furthermore, any anomalous reading for a given station is less accountable to heterogeneity, and thus more likely to represent reality. Additional advantages include a data stacking facility and immediately downloadable field data. As the transient is subject to background noise (which is minimal on Wiveton Marsh) measurements are repeated many times and are recorded and stacked to give a better signal to noise ratio. Once collected in the field, data stored in the receiver may be swiftly and easily downloaded onto a personal computer prior to interpretative modelling (see below).

One of the disadvantages of TEM is that the currents induced by the primary field (above) only become proportional to ground resistivity and time after a few nanoseconds. During this time the induced currents have diffused beyond the immediate subsurface and no resistivity measurement can be made for the top few metres of ground. This is a problem for top–down modelling and so VES measurements (using the 'Offset Wenner' system) were made for the top ten metres. VES measurements were taken shortly after TEM measurements to avoid changes in ground resistivity due to alterations in moisture content. For an account of VES (d.c. electrical resistivity) methods the reader is referred to Barker (1981) or any standard geophysics textbook (e.g. Reynolds, 1997).

Modelling Theory

VES records data in terms of apparent resistivity (ρ_a). TEM records data in terms of voltage, which is then converted to ρ_a using equations given (for example) by Fitterman and Stewart (1986). All values of ρ_a are converted to true resistivity (ρ) via modelling procedures. The relationship between ρ_a and 'true' resistivity (ρ) is a function of the method of measurement, for both TEM and VES. The measured response arriving from any one layer at depth is complemented by responses arriving from other depths too. Thus, the voltage measured at the receiver coil, or between potential electrodes, is a function not only of the resistivity of the layer in which the majority of current is located, but also of the resistivity of other layers in which currents may be present. Due to the locus of induced current at any one time, this effect is somewhat muted for TEM.

Modelling and interpretation of TEM and VES data was undertaken using TEMIX and OFFIX software respectively (Interpex 1988; 1993). Both programs function by matching the field data curve of apparent resistivity versus time (TEMIX) or versus electrode spacing (OFFIX), against a synthetic curve that a model of a layered earth of particular properties and dimensions would exhibit. The modelling procedure assumes layers to be of vertically finite but laterally infinite extent. Once the model and the field data exhibit the same curves, the model is accepted as a representation of the actual. Final model parameters are resistivity versus depth. All models were produced individually prior to construction of a composite (transect) model.

Borehole logging and salinity analysis

The Cley monitoring borehole (Fig. 2) was logged in June 1999 for temperature and conductivity using a Robertson Geologging Portalog. The borehole has been logged for salinity by Anglian Water at least once per year since 1990 (except 1993) and once by the University of East Anglia, in 1992 (Thomas, 1992). Water level in the borehole was recorded using a well-dipper.

The width of the transition zone between freshwater and seawater and the approximate position of the interface should the two fluids be immiscible (i.e. at the 50% seawater/freshwater mixing point) can be calculated. The technique employs a graphical construction in conjunction with the following equation (Todd, 1980):

$$S_r = 100 \left(\frac{c - c_f}{c_s - c_f} \right)$$

where S_r = relative salinity (a percentage); c = salinity at a particular depth; c_s = salinity of seawater; c_f = salinity of freshwater.

Electrical conductivity values for two different depths within the transition zone, seawater and freshwater are derived from the RG Portalog, measurement of seawater and previously collected data (Thomas, 1992) respectively.

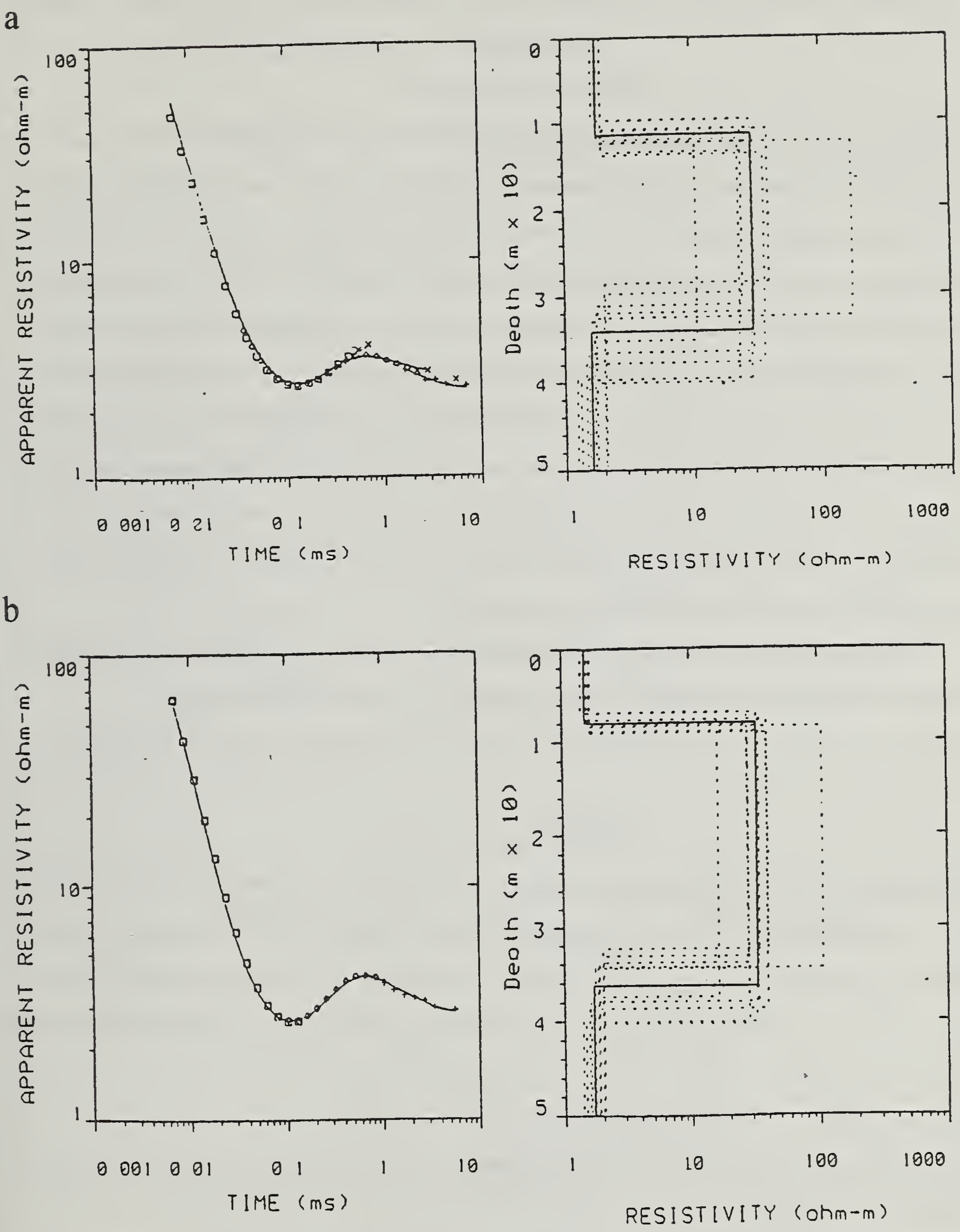


Fig. 6a and b. Examples of TEM modelling results for stations 1 and 2 (Fig. 2). Left panel shows the match between field data and the time/ρ_a curve exhibited by a layered depth/resistivity computer model. Right hand panel shows the depth/resistivity (solid line) with equivalent models (broken lines) exhibiting approximately the same curve (but with higher fitting errors).

RESULTS

TEM and VES results

Two examples of TEM modelling results are presented in Figs. 6a and 6b (stations 1 and 2; Fig. 2). On these figures the left hand graphs illustrate the match between field data points and the time/ρ_a curve exhibited by a layered depth/resistivity computer model. The depth/resistivity model is shown in the right hand graph (solid line) along with equivalent models (broken lines) exhibiting approximately the same curve (but with higher fitting errors). A composite model of depths and resisitivities determined by modelling the TEM data for all stations is shown in Figure 7. The TEM resistivity and depth values for the upper layer (c. top 10 m) of drained saltmarsh correspond well with those values obtained through modelling the VES data. Thus the majority of VES data has been unnecessary for constraining the TEM modelling (see method) and is not presented here. The average fitting error is 4.49% for the TEM data and 8.23% for the VES.

However, not all TEM stations produced convincing models (i.e. 8, 11 and 16) and in these cases VES data has been used to either constrain or confirm TEM models.

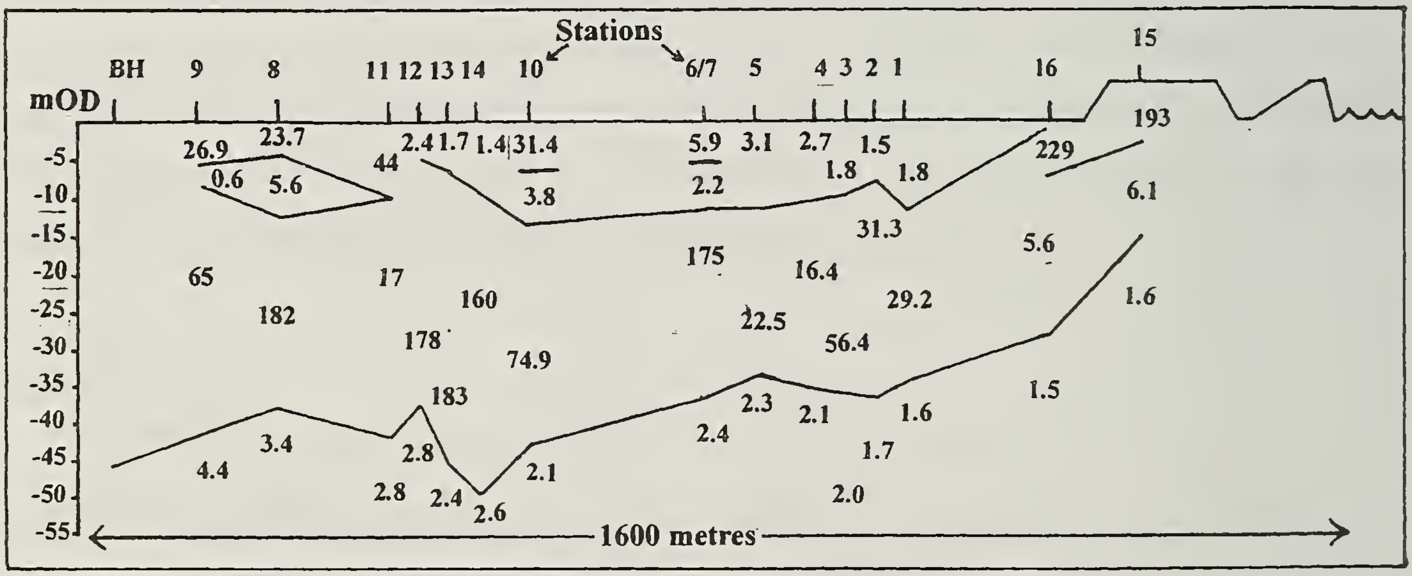


Fig. 7. Composite model of depths and resisitivities determined by modelling the TEM data for all stations (as located in Fig. 2). Station 15 is seaward (i.e. on Blakeney Eye).

Table 1. Depth to top of saline intrusion (point of significant conductivity increase) in the Cley monitoring borehole 1990 to 1999.

Date	**Top of intrusion (m below OD)**
Jun 90	41.9 m
Oct 91	41.4 m
Aug 92	41.9 m
Nov 94	40.4 m
Nov 95	40.4 m
Oct 96	39.9 m
Oct 97	38.9 m
Sep 98	37.9 m
Jun 99	42.4 m

Borehole logging results

The June 1999 borehole log (Fig. 8) shows groundwater conductivity increasing rapidly between ≈-42.1 m OD and the bottom of the borehole (≈-46 m OD). Previous borehole logs of electrical conductivity are summarised in Table 1. Thomas (1992) records the borehole casing extending to -23.4 mOD and the top of the Chalk at -14.4 mOD.

Groundwater head in the Chalk

The groundwater level in the Chalk was recorded at 184 cm below flange or +1.77 mOD at the Cley monitoring borehole. This does not mean that the water level was 1.77 m above sea level, however, as mean sea level (MSL) is referred to Chart Datum. This is a local datum that is not calculated for the Cley area. The nearest Chart Datums exist at Blakeney Bar, Blakeney Harbour, Wells-next-the-Sea, Cromer and Hunstanton. As insufficient data for Blakeney Bar exists for any useful comparisons to be made, and as local conditions preclude

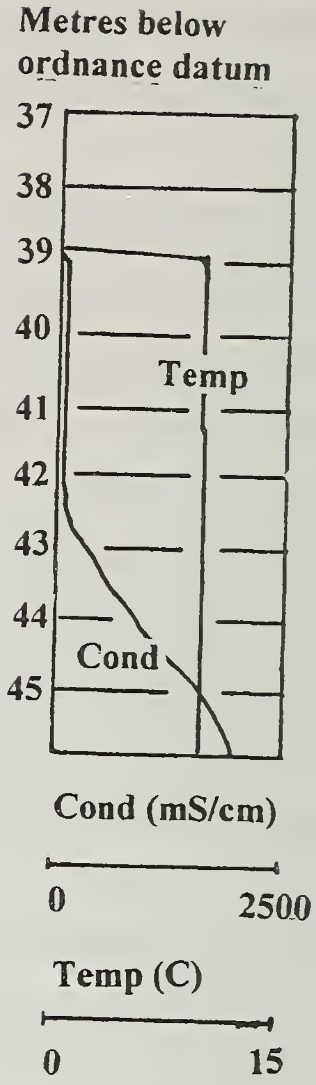


Fig. 8. Geophysical log of temperature and conductivity for the Cley monitoring borehole.

Blakeney Harbour and Well-next-the-Sea from providing valid data, a Chart Datum for the coast north of Cley has been interpolated from tidal values at Cromer and Hunstanton. Calculations indicate that Chart Datum is 3.08 m below OD and, as the average point around which the tide for this area oscillates (i.e. MSL) is 3.4 m above Chart Datum, MSL at Cley is +0.32 m above OD. This means that 0.32 m ought to be subtracted from any head measurement relative to OD to give an accurate figure for head relative to MSL. Thus the head value of +1.45 mOD, is approximately 16m above the surface of the chalk but about 1.5m beneath ground level (non-overflowing artesian conditions).

Drawdown and saline interface width at the monitoring borehole

The borehole at Glandford, abstracting at its maximum annually licensed pumping rate is calculated (after Cooper and Jacob, 1946) to create a drawdown of 0.21 m at the Cley monitoring borehole, subject to assumptions regarding values of transmissivity (T) and storativity (S) (Foley, 1999).

Data for electrical conductivity values within the transition zone were taken from the June 1999 Cley borehole log. Arbitrary depths of -43.4 mOD and -45.4 mOD (-47 and -49 mbfl) within the transition zone were used. Conductivity values for these points are estimated to be 3100 and 9400 $\mu S\ cm^{-1}$ respectively ($\pm 100\ \mu S\ cm^{-1}$).

Using conductivity values of 450 and 35 000 $\mu S\ cm^{-1}$ for fresh and seawater respectively (Thomas (1992) (freshwater); Foley (1999) (seawater)), the point of 50/50 fresh/seawater mixing and the thickness of the transition zone have been calculated. The 50% point is at - 46.5 mOD ±0.25 m (just below the bottom of the borehole). The thickness of the transition zone from 1% to 100% seawater is estimated to be 7.25m ±0.50m (-40.5 mOD ±0.25 m to -47.75 mOD ±0.25 m).

Tidal oscillation

The tidally induced alteration of head in a coastal artesian aquifer at a distance, x, from the shoreline may be calculated using the following equation (after Jacob (1950) and Ferris (1951)):

$$h = h_0 \exp(-x\sqrt{\pi S/t_0 T}).\ \sin(2\pi t/t_0 - x\sqrt{\pi S/t_0 T})$$

Where h = tidally induced head alteration at some distance x from the shore (m); h_0 = tidal amplitude (m); x = distance from shore (m); t_0 = period of tidal cycle (d); t = time referred to beginning of tidal cycle (d); S = storativity (dimensionless) and T = transmissivity ($m^2\ d^{-1}$).

The equation assumes a bulk hydraulic conductivity of $\approx 100\ m\ d^{-1}$. Should any large fractures be present, tidal fluctuations may play a greater role in mixing than calculated. Other assumptions are that the aquifer is artesian (it is) and that pore fluids are assumed to be of uniform density, although that they are not does not unduly affect the results (Cooper, 1959).

The tidally mediated head change versus distance from shore in the Chalk at Cley is shown in Figure 9. The plot assumes a maximum difference in tidal height (i.e. 0.5 of a tidal cycle) and tidal range of ≈3.7 m (Foley, 1999). The effect of tidal influence beyond 100 m from the shore is negligible.

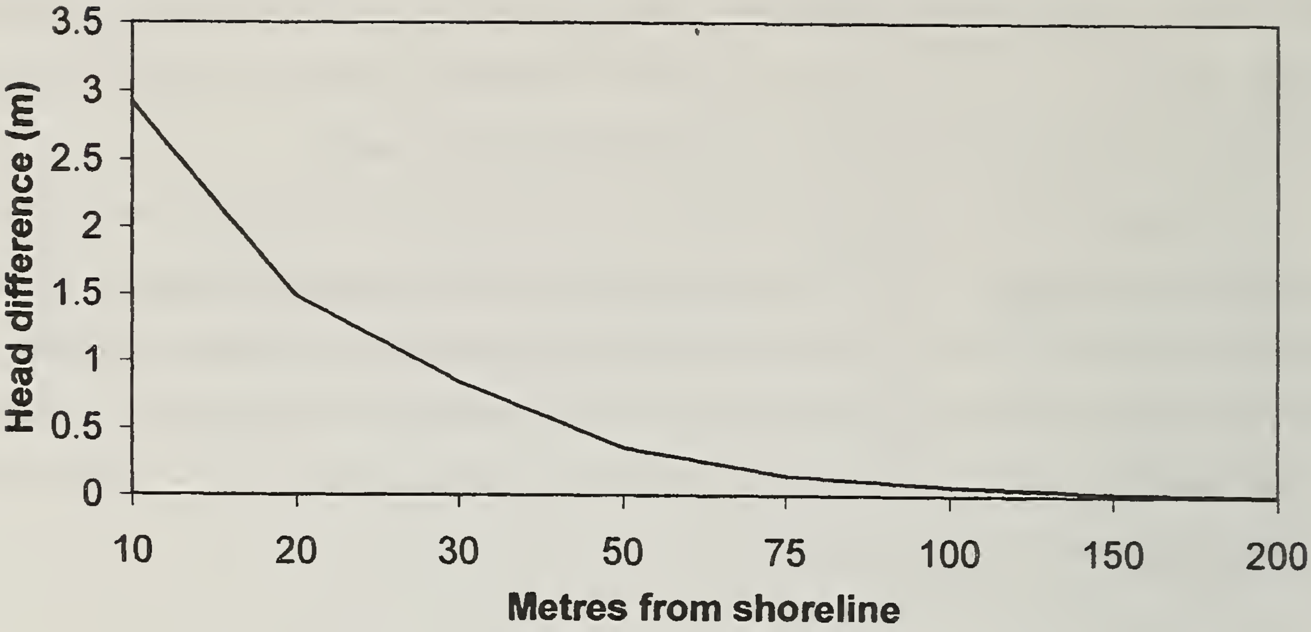
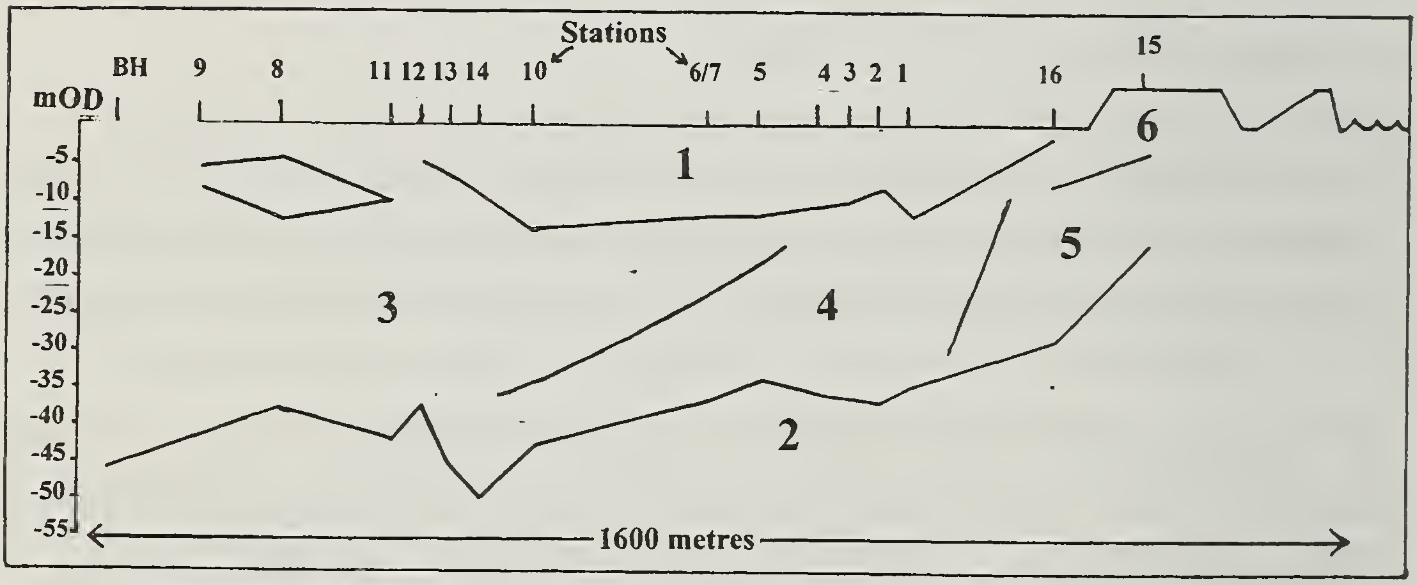


Fig. 9. Tidally mediated head fluctuations in the aquifer at Cley.



Key:
1) Confining Holocene deposits
2) Seawater intrusion
3) Fresh groundwater
4) Brackish groundwater
5) Highly saline groundwater
6) Freshwater lens present in Blakeney Eye

Fig. 10. Interpretation of resistivity results from modelling. Station 15 is seaward (i.e. on Blakeney Eye).

DISCUSSION

TEM data and modelling

Six zones of contrasting resistivity can clearly be defined (Fig. 10). These zones are the intrusion itself; fresh, brackish and highly saline groundwater zones; confining Holocene deposits and a freshwater lens in Blakeney Eye. Furthermore, modelling seems able to differentiate between a relatively sharp interface (stations 11-6), thicker zones of mixing underlain by more saline waters (stations 5-1), and even between zones varying in resistivity by only 5 or 6 Ωm (e.g. stations 15 and 16). This suggests that the vertical resolution of the method is good and that the distinction between, for example, the brackish zone and the saline zone (stations 5-1), is a real one.

Generally the TEM data is of good quality and the final composite model is simple to interpret. Confidence in the model may be drawn from three quarters:

1. The error figures expressing the correlation between synthetic model and field data curves are low (mean = 4.49%). This reflects the modelling error, not the error between the model and the subsurface environment. Thus, although the error figures are a proxy for the actual error, the modelling procedure is shown to be reliable.

2. Because most models adjacent to one another vary only marginally there is a greater probability that the individual models are a faithful representation of the environment (the possibility of a consistent error is negated by point 3.) Furthermore, any model that does not fit this pattern (e.g. station 11) is made obvious.

3. There is good correlation between TEM and borehole data. Both the Funnell and Pearson (1989) and the Andrews *et al*., (2000) boreholes in the west, and the Cley monitoring borehole in the south, support the TEM models.

Equivalence and suppression

Equivalence arises because of the constant relationship between the resistivity and thickness of any layer. Therefore a number of equivalent models may fit the observed data and care must be taken to analyse equivalence during modelling. Both TEMIX and OFFIX possess an 'Analyse equivalence' function that was applied to all models (see Fig. 6 for example).

Equivalence varies depending on the resistivity relationship between layers. For example, a three layered earth with a conductive middle layer will exhibit type 'S' equivalence (Reynolds, 1997), where the relationship h_2/ρ_2 is constant (h_2 is thickness, ρ_2 is resistivity). In contrast, a three layered earth with a resistive middle layer will exhibit type 'T' equivalence, where the relationship $h_2.\rho_2$ is constant.

However, TEM subdues the equivalence problem because measured voltages are related to current strength at, largely, one depth (see above): sensitivity to upper layer resistivities are lost over time as currents penetrate deeper (Fitterman, 1986). The situation at Cley, where the middle layer is resistive, is resolvable with TEM. Fitterman *et al.* (1988) concluded that, in such a situation, equivalence can be resolved for h_2 but not for ρ_2. Stations 10 and 3 may be examples of failure to resolve ρ_2 equivalence. Examination of Station 10 reveals that at least one of the equivalent models would more closely match the stations either side, probably for only a marginal increase in error. This does not affect the position of the saline interface greatly, nor the position of the base of the Holocene, both of which are subject to some borehole control anyway.

Suppression of a layer occurs when the contribution of that layer to the sounding curve is small (Burren, 1998). This is the case when layers are either thin or have little resistivity contrast with adjacent layers. We cannot determine the magnitude of this effect at Cley.

Vertical resolution: VES data integration and resolution of the surface layer

Based on corroborating borehole evidence, the vertical resolution of the TEM data appears to be good, even for the top ten metres. This may be because the surface layer, a relatively recent marine clay, is unusually conductive (typically <2.5 Ωm). Therefore, induced currents may still be present when the 'late' time linear relationship is achieved. The only layer that the TEM method could not resolve was the thin (<0.5 m) vadose zone at the very surface (not shown in Fig. 7). For these reasons, the VES modelling constraint was used for two stations only (11 and 16) where the TEM result is spurious and the VES modelling has a low error figure:

Station 11 is located where the saltmarsh meets the high ground in the south (Fig. 2). Therefore, it may be expected to show deviation from the adjacent station (12), which is located further onto the marsh. Because of this, the top layer of the TEM model was constrained with the VES resistivity (44 Ωm; 2.25% error). This procedure disregards the 1m surface layer (17 Ωm) identified by the VES modelling. The thickness of this layer was not constrained because the VES result gives a thickness ≈20 m. Due to current penetration considerations this cannot be considered reliable.

The final TEM model is resolved with an error of 2.36%. This is attractive but the underlying layer has a resistivity of 17Ωm, which is an order of magnitude different to the adjacent station (12). This station is thus suspect.

Station 16 was given a constrained surface layer thickness of 1 m and resistivity of 2 Ωm, based on the assumption of a thinning layer of saltmarsh at the foot of Blakeney Eye. This constraint is borne out to some extent by the VES, which shows a top layer of 2 m and 18 Ωm. However, the final result is satisfactory: fresh, brackish and saline groundwater zones are delineated.

Other stations of note (Figs. 2 & 7) include the following:

Station 10: differs from other stations in the central marsh area in that it has a significant thickness of more highly resistive material at the surface. This is identified by the TEM and corroborated by the VES, and is therefore accepted as accurate.

Stations 8 and 9: (see Fig. 7) show strong dissimilarity between the optimum TEM models and the VES models. Constraint of these models leads to high TEM modelling error. VES data contains error of 9.17 and 15.57% respectively, whereas TEM modelling produces error figures of 3.16 and 5.90%. This may be due to lateral variation but further work is required to resolve the discrepancy.

Stations 15 and 16: Station 15 rests atop Blakeney Eye. The VES confirms that at least the top 5 metres consist of a highly resistive layer. Below this the TEM data is accepted as it delineates a further two layers that correspond with layers at station 16, whereas the VES identifies only one. Both stations exhibit top layer values that, at c. 200 ohm metres, are too high for saturated gravels (N. Chroston pers. comm., 2000). However, the top layers identified at both stations extend beneath the water table. Thus the TEM values for the top layer probably represent both saturated (freshwater) and unsaturated conditions.

To permit further comparison, modelling for one station (8) was undertaken both with and without VES constraint. The results are shown in Figure 11. Modelling with constrained data could not produce a matching curve with an error less than 19%. This compares unfavourably with an unconstrained error of 3.16%. It should be noted that the error associated with the VES data is a typical 9% (avg. = 8.23%). Constraint ensures propagation of this error into the TEM model.

Resolution at the saline/freshwater interface:

It is artificial to suggest that such a clear boundary between fresh and saline groundwater, as shown in Figure 7, exists in reality. This is illustrated by the calculation of the thickness of the transition zone at the borehole and is noted throughout the literature. Because the modelling assumes uniform resistivity for each layer, which condition is not met by the transition zone, it cannot be modelled as a single layer. Thus the sharp boundary depicted represents a point somewhere within the transition zone.

Hydrogeological controls on intrusion at Cley

Borehole logs dating back to 1990 record that the position of the interface is capable of moving vertically (Table 1). Such fluctuations will be caused by variable recharge and local pumping rates. Overall, however, there appear to be no great variations from an average value of -40.5 mOD. Variations in recharge, pumping and tidal oscillation will also increase mechanical dispersion, thereby influencing the width of the interface (calculated to be ≈7 m at the monitoring borehole). Mechanical dispersion will be augmented by molecular diffusion due to the concentration gradient between saline and fresh water. It should be noted that, due to density differences, saline water entering the borehole at any point may accumulate toward the bottom. This may give an incorrect impression of the position of the interface in the surrounding aquifer.

The effect of pumping from Glandford pumping station, 2050m SSE of the Cley monitoring borehole, is to decrease the freshwater head at the borehole. Should the abstraction borehole be pumped at a constant rate to the maximum yearly license (i.e. at a rate of 4110 m^3 d^{-1} or 1 500 000 m^3 a^{-1}), drawdown at the monitoring borehole is calculated to be 0.21 m after one year. From density considerations alone, this is sufficient to cause a rise in the interface at the Cley borehole of approximately eight metres. Overall, the

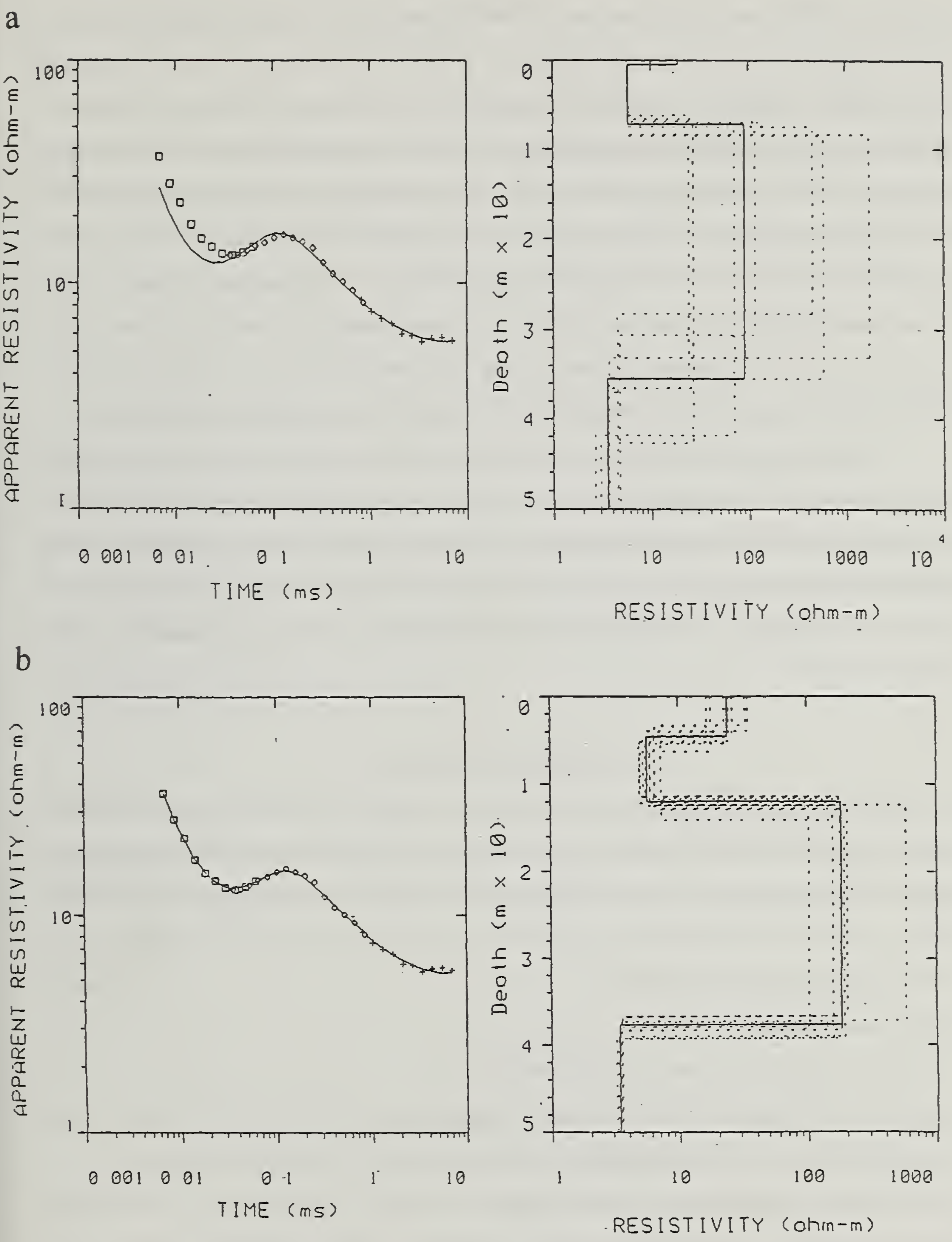


Fig. 11. a) Vertical electrical sounding (VES) constrained model (station 8), and b) VES unconstrained model (station 8). Modelling with VES constrained data could not produce a matching curve with an error less than 19%. This compares unfavourably with an unconstrained error of 3.16% (see text).

calculated width of the interface at the borehole seems reasonable and is unlikely to be > 30m as suggested by Thomas (1992). However, a thicker mixing zone does develop toward the coast (Figs. 7 and 10). The water underlying the Holocene deposits, from station 5 northward and extending beneath Blakeney Eye, becomes increasingly saline. The transition to this zone, which is laterally distinct, may be equivalent to the interface identified by Burren (1998) and which he interprets as the main intrusion itself (although this may be the case at Morston). Increased mixing is due to tidal influence, a steepening interface resulting from a seaward decrease in freshwater head and a concentration of freshwater flow leading to enhanced vertical motion. Note that although tidal oscillations and gradients have been calculated with respect to the shoreline, the river Glaven is also subject to tidal imbalance.

A highly resistive surface layer is present at Blakeney Eye (see Fig. 7). As this layer extends beneath the water table, it may be concluded that a freshwater lens floats upon the saline water body. This situation is similar to that identified by Holman and Hiscock (1998) in the dunes protecting the Thurne catchment (Norfolk) from inundation by the sea. The lens is likely to contribute to the development of the brackish zone by providing another source of freshwater flow.

CONCLUSIONS

The TEM method has produced data of quality sufficient to locate the saline intrusion beneath the drained coastal marsh at Cley. Geophysical modelling permits construction of a simple conceptual model in which the following six distinct geoelectric units are identified:

1. The confining Holocene deposits.
2. The saline intrusion.
3. A zone of fresh groundwater in the south.
4. A zone of mixing/brackish groundwater in the north.
5. A highly saline zone of mixing beneath Blakeney Eye.
6. A freshwater lens present in Blakeney Eye.

The geophysical models are confirmed by a variety of borehole information that identifies the base of the Holocene and the position of the intrusion. Further confidence in the interpretation draws upon low modelling error figures and concurrence between adjacent models.

The problems of equivalence and lateral variation, frequently associated with geophysical modelling, are reduced. However, some limitations arise from the modelling procedure. In particular, the sharp distinction between the intrusion and the layer above is a product of the modelling. This boundary is unrepresentative and should be viewed with caution. The method also failed to delineate all lithologies: several metres of glacial material beneath the Holocene remain indistinguishable from the Chalk. This illustrates the overriding influence of pore fluid conductivity on the TEM method.

VES data is useful on occasions, but is sometimes contradictory and often has a high associated error. It has been generally superfluous to identifying the original target.

The implications for resource management do not go beyond that practice currently pursued. If assumptions regarding the hydraulic properties of the aquifer are correct, it is true that abstraction at Glandford does result in a rise in the position of the interface. However, water quality at Glandford suffers from very little chloride contamination, indicating that the status quo is acceptable.

ACKNOWLEDGEMENTS

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A NOTE ON THE OCCURRENCE OF *ECHINOCARDIUM CORDATUM* FROM THE RED CRAG, PLIOCENE, EAST ANGLIA.

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ABSTRACT

The occurrence and distribution of ***Echinocardium*** *in the Red Crag is described and discussed in relation to accompanying molluscan assemblages and interpreted sedimentary structures.*

INTRODUCTION

The highly collectible molluscan macrofauna of the East Anglian Red Crag has long been documented and described. It is clear from a study of both the sedimentology of the deposits and the fauna itself, that most of the shells are derived to a greater or lesser extent, having been transported by currents from their living positions to be deposited as a shelly sand sediment. One of the problems facing researchers has therefore been to distinguish the extent to which transport and reworking have affected the assemblages found today.

Just occasionally, however, relatively undisturbed faunas can be found, and two such faunas, characterised by the presence of *Echinocardium cordatum* are described here.

E. cordatum is an irregular, atelostome, spatangoid sea urchin, commonly called the 'sea potato'. It is bilaterally symmetrical, heart shaped, usually about 60mm long but up to 90mm, with brittle spines, dense like fur. It lives burrowed 80-150mm deep in sand, feeding on detritus and small animals. Today it is found widely in the lower mid-littoral to infra-littoral fringe, but also sublittorally to around 200m depth.

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SAMPLING LOCATIONS

Locality 1: Walton on the Naze

The Red Crag sequence below and to the north of the cliff top tower at Walton on the Naze (Fig. 1; TM 266234) is broadly interpreted as showing four phases of megaripple advance, successive megaripples being banked up against and partially overlying an earlier one, the first and oldest being at the southern end of the section and younger ones to the north. The ripples migrated across a scoured London Clay surface, hollows in the surface being already partially filled with Crag sediments and characterised by intermittent lag deposits (Dixon, 1977).

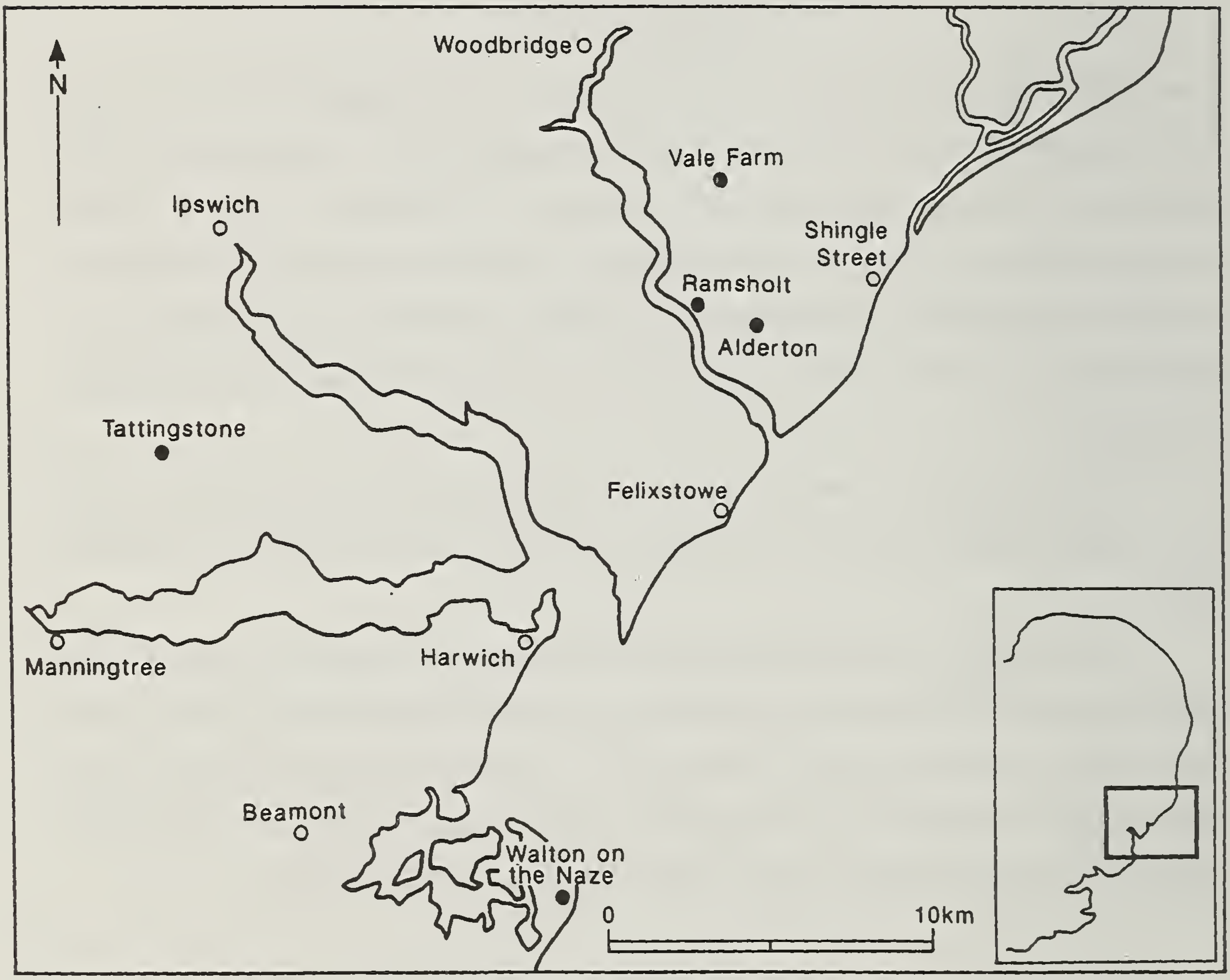

Fig. 1. Red Crag localities with horizons bearing *Echinocardium cordatum* (filled circles). Other towns (open circles).

The assemblage described here came from near the base of the second megaripple set. The sediment is a poorly stratified, moderately well-sorted fine sand, but with a higher proportion of finer material and smaller coarse fractions than are commonly seen in the Red Crag. The horizon does not outwardly appear to be rich in fossils and may easily be overlooked by the casual collector considering the richer pickings elsewhere.

The horizon is 0.3-0.5m thick, and is interpreted as bottom sets that accumulated in the trough between two megaripples.

Locality 2: Ramsholt

The Ramsholt assemblage (Fig. 1) comes from a small pit away from the tow-path, on the northern edge of a wood (TM 307416), and is much overgrown. The sample came from a relatively poorly-sorted laminated silt with shelly sand intercalations, which overlies, and is overlain by shelly sands. Three dimensional relationships are unclear, but comparable beds in the nearby cliff sections indicate that the shelly sands are probably megaripples (viewed longitudinally), while the silts may represent bottom sets and exhibit small-scale ripples.

Other occurrences

Small fragments of *Echinocardium* have been found in other Red Crag horizons, but the poor state of preservation and degree of comminution show clearly that transport has occurred and the test fragments have been washed in.

1. Walton on the Naze: found in several shell avalanche lobes at the base of megaripples in *Glycimeris* shell gravel assemblages.
2. Tattingstone (Fig. 1; TM 143373): in a highly bioturbated micaceous silty sand associated with a *Mya arenaria* / *Mytilus edulis* assemblage, with occasional Mya in the life position. Unfortunately, re-evaluation of this important site, where Red Crag rests unconformably upon the southernmost occurrence of Coralline Crag, is not possible since it was flooded by the Alton Water reservoir.
3. Alderton (Fig. 1; TM 328412): channel-bedded sands with a *Mytilus* / *Spisula* assemblage.
4. Vale Farm (Fig. 1; TM 317456): trough cross-bedded sand with a *Mytilus* / *Spisula* assemblage.

THE FAUNA

Although *Echinocardium cordatum* has been found as small fragments from other horizons over the Red Crag outcrop, these two horizons are unusual in that quite large pieces of test have been collected from then. Indeed, Markham (pers. comm.) reports that he has found complete tests with spines still attached from the Walton horizon. This indicates that transport has been minimal and post-death burial prompt. Usually, disintegration of *Echinocardium* is rapid upon death, because the test is fragile and the spines rub off easily.

As well as *Echinocardium,* both assemblages are characterised by high percentage frequencies of *Abra alba*, and commonly contain articulated valves and juveniles of other species. The frequencies of the most common species, using counting methods used by Dixon (1977) and Norton (1967), are given in Table 1.

Abra alba is today a widespread boreo-lusitanic species found between extreme low water spring tide (ELWS) -120m water depth, but optimally in about 20m of water in muddy sand and mixed muddy substrates. It has well documented community associations, which include *E. cordatum* (e.g. see Thorson, 1957).

At Walton, the assemblage contains unusual species not commonly found elsewhere in the Red Crag including *Mysella bidentata* (sublittoral muddy sand), *Thracia phaseolina* (sublittoral mud-tolerant), *Musculus costulata* and *M. discors* (low shore epifauna). Relatively low frequencies (for the Red Crag) of *Glycimeris* and *Venerupis* occur, and many of these are juveniles. Other species also occur as juveniles, eg. *Cardium edule* and *Mya arenaria*. Frequencies of the extinct *Ensis waltonensis, Nassa granulata* and *Turbonilla internodula* are also significant.

At Ramsholt, these "unusual" species do not occur, but, characteristic of the later Red Crag assemblages, there is a high frequency of *Spisula spp*, many of which are articulated and possibly in their life position. *Spisula* is clearly the dominant genus and it is primarily *S. ovalis*, with a smaller proportion comparable to *S. obtruncata* and some *S. constricta* (all as figured in Wood, 1848). As such, they are all considered extinct and are therefore 'uninformative'. However, Long (2000) considers these species to be ecophenotypes of *S. solida*, which is a shallow water (ELWS-40m) bivalve, living in fine to coarse sand and shell gravel and, as here, often occurring in large numbers living together. Extinct *Cardium angustatum* forms a significant frequency, as do many weathered (and unidentifiable) *Cardium* hinges.

Table 1

Percentage frequencies of the most commonly occurring molluscan species in the Ramsholt and Walton *E. cordatum* horizons. All species recorded were divided into 'ecological groups'; the totals for each group are also given.

	Ramsholt	
Walton		
Low shore epifauna		
Calliostoma conuloides	-	1.2
Tectura virginea	-	1.2
Musculus costulata	-	2.4
Mytilus edulis	1.7	<1
Total	**1.7**	**6.0**
Intertidal sandy shore		
Mya arenaria	1.1	<1
Total	**1.4**	**<1**
Infralittoral		
Zirfaea crispata	-	2.4
Total	**<1**	**2.4**
Sublittoral shell gravel		
Glycimeris glycimeris	<1	3.0
Venerupis sp	<1	2.4
Total	**2.2**	**5.4**
Sublittoral muddy sand		
Abra alba	16.3	22.4
Mysella bidentata	-	3.6
Total	**17.5**	**26.0**
Sublittoral clean sand		
Total	**<1**	**-**
Sublittoral mud tolerant		
Turitella incrassata	1.9	6.1
Thracia phaseolina	-	6.1
Total	**1.9**	**12.2**
Habitat unknown		
Astarte digitaria	<1	1.2
Various substrates		
Chlamis opercularis	<1	1.2
Venus ovata	<1	2.4
Total	**1.1**	**5.1**
Extinct		
Nassarius granulata	<1	7.3
N. propinqua	-	1.2
Natica hemiclausa	<1	1.2
Turbonilla internodula	-	3.6
Cardium angustatum	10.1	-
Ensis waltonensis	-	4.2
Macoma praetenuis	2.1	-
Pholas cylndrica	-	3.6
Spisula spp.	43.6	6.0
Total	**58.0**	**31.3**
Total individuals	**371**	**165**
Total species	**36**	**31**
% of one individual	**0.27**	**0.61**

The *Abra* assemblages seem to have developed at the expense of certain other typical Red Crag species. In particular, *Aloidis gibba*, which is common elsewhere throughout the Red Crag and has similar ecological preferences, is virtually absent. Clean sand species (eg. *Dosinia exoleta*), epifauna (eg. *Buccinum undatum*) and *Astarte spp* are also markedly reduced in frequency, if present at all.

DISCUSSION

The widespread molluscan faunas found generally in the Red Crag are dominated by a succession from *Glycimeris* to *Venerupis* and then *Mytilus* shell gravel assemblages, which, in turn, are overlain by *Mya*-rich littoral assemblages (Dixon, 1977). The shell gravel faunas are associated with megaripples characteristic of fairly high intensity currents in the lower flow regime (Dixon, 1979). The related bed-forms – reverse flow ripples, mud drapes, imbrication, reactivation surfaces and more – make the Red Crag a classic case study. The widespread occurrence of shell lags and shell avalanche lobes, combined with clear evidence of current sorting of shells based on their shape, size and hydrodynamic behaviour, and the huge amount of comminuted, worn and abraded shell material means that interpretation of shell assemblages must be treated with caution. However, studies of the assemblages as a whole, based upon detailed sampling (Dixon, 1977) indicate that in general the fossil assemblages do reasonably well represent the original communities, even though transported.

The *E. cordatum* assemblages described here are therefore exceptional, for all the evidence – the state of preservation of the sea urchin tests, articulated valves, the preservation of delicate and fragile shells, the possible life positions of shells – indicates that these shells have not been transported. They possibly represent two of the uncommon and truly autochthonous assemblages to be found in the Red Crag. The author suspects that continued careful search of appropriate horizons will yield further examples of these unusual assemblages.

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GEOLOGICAL SOCIETY OF NORFOLK WEBSITE

The Geological Society of Norfolk has recently set up a website which can be reached at:

http://www.uea.ac.uk/env/gsn

Details of GSN activities can be found here including:

- Information on the aims and constitution
- Forthcoming meetings, lectures and fieldtrips
- Details of GSN projects
- Details of GSN publications, including instructions for authors
- Information on significant recent finds
- Hot links to other geological websites

A SHORT NOTE ON THE DISTRIBUTION OF *ECHINOCYAMUS PUSILLUS* IN THE RED CRAG

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INTRODUCTION

Echinocyamus pusillus is an irregular, gnathostome, clypeasteroid sea urchin that has attracted the attention of collectors on account of its 'cute' appearance – its small size, and its widespread distribution in the Red Crag. It is extant today, being commonly called the 'dwarf green urchin' or 'pea urchin'. It is found commonly offshore around the British Isles, being a generally boreo-lusitanic species, and knowledge of its habitat and ecology can therefore be directly applied to the Crag.

The body of *E. pusillus* is short, about 10-15mm at most, with very short, close, dense spines and in life is a grey to green colour. It lives off-shore from below extreme low water spring tide (ELWS) down to 500m, but is sometimes found on the low shore or may be washed up onto the shoreline. It inhabits coarse sand or gravel and, in particular, shell gravel, where it nestles down between the shells to protect itself from currents. It has sucker discs on its tube-feet to help it move among the shell gravel.

DISTRIBUTION

Although it occurs widely in the Red Crag, the distribution of *E. pusillus* is only occasionally referred to by earlier authors. Spencer (1957; 1971) gives some details, commenting on a small number of locations where it is particularly abundant – i.e. Walton-on-the-Naze, Shottisham and Alderton. Otherwise, it is usually simply included in species lists as being 'present'. Spencer also states that it is rare from the Coralline Crag. Markham (pers. comm.) has recorded it from a borehole into the Coralline Crag

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and also from the "*Scrobicularia* Crag" at Chillesford (TM 383524) and at Aldeburgh brickyard (TM 452572). It does not seem to occur anywhere else in the Norwich Crag.

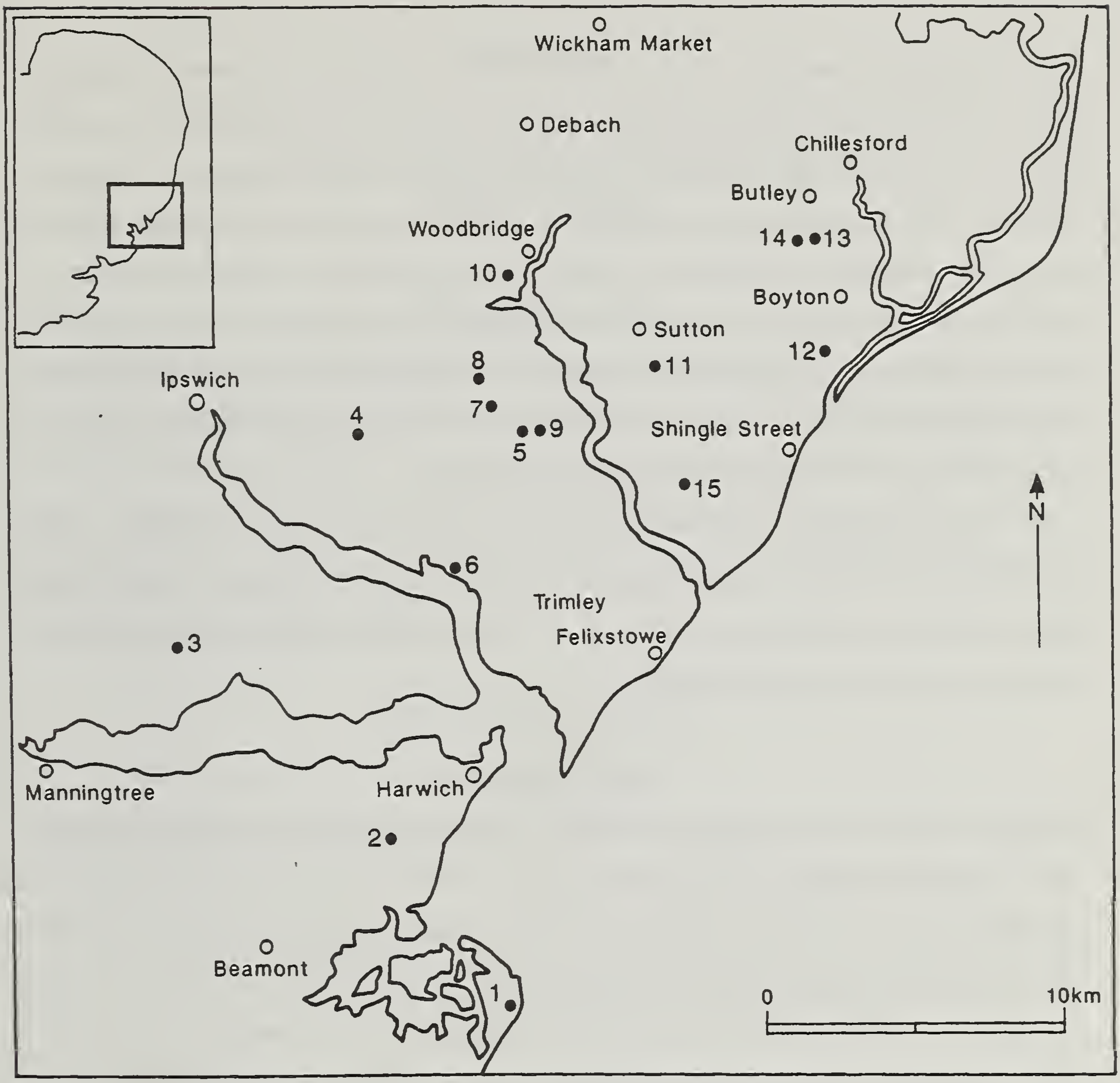
Collecting over the last 30 years has shown that geographically *E. pusillus* occurs widely and consistently over the Red Crag area – one or two can usually be found at many localities, and keen collectors will know that it is extremely prolific at certain horizons at some localities, to the extent that 100-200 specimens can be collected by sieving in a relatively short space of time. This relative abundance alters the degree of significance of *E. pusillus* from a very minor component of the invertebrate macrofauna to one of importance.

Close examination and careful sampling reveal that there is a pattern to its occurrence. The majority of finds are from horizons associated with megaripples or sand waves. At Walton-on-the-Naze, Alton and Stratton Hall, for example (see Fig. 1), it is found in shelly coarse sand foresets but is more common in shell avalanche deposits. Less commonly they are found in medium sand bottom sets. The associated molluscan assemblages of the ripples are dominated by high percentage frequencies of shell gravel species (>30% of individuals) such as *Glycimeris* and *Venerupis*.

INTERPRETATION

The interpretation is that these animals colonised the ripples when water conditions allowed. *Glycimeris*, for example, is well adapted to the physically rigorous environment found on a current-swept seafloor. Water depths at Walton are estimated to be around 20-25m but were less than this further to the north, in later Red Crag deposits. During phases of high current activity, during storms, for example, or because of tidal scour, the animal communities were swept away from their living positions to be deposited as foresets, contributing to ripple migration. As shell accumulations became unstable on the lee face of the ripple, they avalanched down to form shell lobes extending out into the trough regions.

It is clear from this sedimentary environment that winnowing and transport must have played a significant role in modifying assemblages between life and final burial. However, the not uncommon presence of articulated valves of *Glycimeris* and other species (eg. *Aloidis gibba* and *Cardita corbis*) indicates that winnowing may have been fairly limited at times and that by and large fossil assemblages found today are fairly representative of the communities that existed at the time.



1. Walton-on-the-Naze:	megaripple bottomsets megaripple foresets (upper and lower)	shell avalanche
2. Little Oakley:	megaripple foresets	
3. Alton Dam Site:	megaripple foresets	shell avalanche
4. Purdis Farm:	megaripple bottomsets (two horizons) medium scale ripple	
5. Newbourn Church:	lower foresets	
6. Stratton Hall:	shell avalanche	
7. Waldringfield Plantation:	megaripple foresets	
8. Waldringfield Heath:	megaripple foresets	
9. Street Farm:	lag deposit at ripple base	
10. Suffolk Seed Stores:	megaripple foresets	
11. Vale Farm:	channel lag trough cross bedded unit (two horizons)	shell avalanche
12. Cauldwell Hall:	bottomsets	
13. Daffodil Woods:	channel lag	
14. Capel Green:	shell avalanche	
15. Alderton:	trough cross bedded unit	

Fig. 1. Red Crag localities with horizons bearing *Echinocardium pusillus* (filled circles). Other towns (open circles).

Elsewhere, especially in the north-eastern part of the Red Crag area, at Alderton, Vale Farm and Daffodil Woods for example (Fig. 1), *E. pusillus* is found in coarse shelly lenses and lag deposits associated with channel and trough bedforms. Adjacent sediments often contain small or medium scale ripple structures with laminated silts and muds and commonly contain trace fossils. The sedimentary structures indicate a nearshore or infralittoral environment with a significant tidal influence. This is supported by the presence of *Mytilus-Macoma-Spisula* molluscan shell gravel assemblages. Although interpreted water depths are less than 5m, the shell gravel habitat nevertheless seems to have provided ideal conditions for *E. pusillus*.

It seems, therefore, that the general environmental conditions prevailing during Red Crag times provided entirely suitable habitats for the development of shell gravel faunas. These, in turn, were colonised by *Echinocyamus pusillus*, resulting in the widespread distribution that is found today.

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REPORT OF SOCIETY FIELD MEETINGS IN 2000

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INTRODUCTION

To improve attendance at field meetings the Society organised field meetings jointly with the Suffolk Naturalists Geology Group under the auspices of Bob Markham. The following reports refer only to these joint meetings, although there were others that Society members were able to attend, some of which have been reported in the Society Newsletters. An account of the Society's 50th Anniversary geological excursion to Bawdsey is given in Dixon (2000).

THE GIPPING VALLEY

Saturday 24th June

The aim of this field day was to examine the Pleistocene succession in the huge Great Blakenham chalk and clay pits. Already in use as a landfill site, access will be severely restricted in the future and the sections soon lost forever. Detailed descriptions of this section are given by Allen (1982; 1988), and in the excellent papers by Green and McGregor (1999), Rose *et al.*, (1999), Rose *et al.*, (2000) and Rose (2000).

We started at the top of the succession, looking at the Lowestoft Formation tills, of Anglian age. Of particular interest was the wide range of erratic types; several different ammonites, belemnites, oysters and *Gryphaea* were found, as well as a variety of rock types, including Spilsby Sandstone and Kimmeridge Clay. Earlier workers identified two main distinct till types ('Lowestoft' and 'Gipping') on the basis of colour. However, both tills seem to have been formed under similar conditions and, although granulometric data shows some variation, which may account for the colour differences, classic fabric and clast analyses have demonstrated that they probably represent facies variations of one lodgement till sheet.

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A variety of glaciotectonic disturbances of the underlying beds, including thrusts and deflected convolutions, indicate that ice sheet movement was from the north-west.

The underlying Palaeosols Layer comprises primarily the Valley Farm Rubified Sol Lessivé, where a concentration of clay and haematitic iron suggests an illuvial soil horizon of pedogenic origin in a temperate environment. Subsequent periglacial processes have deformed this to give an 'arctic structure'.

The Kesgrave Sand and Gravel, on which the palaeosol is formed, is now interpreted as part of a Pastonian terrace of the former course of the Thames. The 'Kesgraves' comprise nearly 4m of yellowish, flint/quartz/quartzite-rich sands and gravels. Sedimentary structures in the lower part of the unit indicate fluviatile transport from the southwest.

The stratigraphic position of the Creeting Sands, c.11m thick, has also long been a problem, and certain aspects of its interpretation remain enigmatic. They are clean, white, unfossiliferous, well-sorted fine and medium grained micaceous sands. Well-developed small and medium scale ripple bedding is characteristic, with flaser bedding and channelling evident. The interpretation is of tidal estuarine environment, maybe a beach, sandflat or nearshore deposit, although there is a wide variation of palaeocurrent directions (rather than the bi-polar distribution expected from a tidal environment). The sands are correlated with the Chillesford Beds, possibly Bramertonian in age. The composition of gravel stringers again suggests derivation from a proto-Thames drainage system.

The College Farm Silty Clay beds towards the top of the Sands contain a *Pinus* woodland vegetation with areas of heathland, and is interpreted as a possible high tidal flat deposit.

Underlying the Creeting Sands is the so-called "Red Crag Basement Bed", commonly c.30cm thick. This is a red sandy conglomerate cemented by iron oxide, comprising flint pebbles with abundant phosphatic nodules and containing sharks teeth and bone fragments. Correlation with the base of the Red Crag is based really upon general similarities, though there are significant differences between this deposit and, for example, the Battisford pebble bed or basal phosphatic pebble beds in the Red Crag itself.

The Basement Bed rests upon Gonioteuthis granulata chalk at Great Blakenham, and, further to the east, upon the London Tertiary series. The Chalk received only a cursory examination, mainly because it was getting rather late in the afternoon.

WEST RUNTON

Saturday 22nd July

The section of cliff and foreshore studied was from Woman Hythe east to Wood Hill, and west for about 300m. Exposure was good and, as the tide receded, we were able to examine the complete succession from the chalk up through the pre-Pastonian/ Pastonian Stone Bed and Weybourne Crag, the Beestonian West Runton Freshwater Bed, the *Leda myalis* Bed to the Bacton and Mundesley Sands. Overlying these Cromer Forest Bed Formation pre-glacial deposits lies the 'Contorted Drift' (Laminated Diamicton), displaying spectacular glacio-tectonic rafts and deformations belonging to the Anglian glaciation, and the enigmatic 'sand basins'. Other points of interest were the site of the West Runton elephant, and several flint paramoudras exposed on the foreshore.

Fossil collecting was easily possible from the Weybourne Crag, exposed above low tide level on the foreshore, *Macoma balthica* and *Arctica islandica* being particularly common. The fauna of the Freshwater Bed was also studied, although the shells are rather friable. The faunas are well documented in a number of papers.

Of particular interest to participants were not only the interpretations of palaeoenvironments but also the indications of sea level changes that the pre-glacial sequence shows and the lateral variability of some of the individual beds. Discussion of the mechanics of the deformation of the Contorted Drift and the origin of the huge Chalk erratic rafts also occupied some time!

Descriptions of this coastal section are so well written in the literature that readers are referred to them for detail: Gibbard and Zalasiewicz (1988), Stuart (1991), Hannam *et al.*,(1996) and Lewis *et al.*, (2000).

COVEHITHE

Saturday 26th August

The exposure was good, as would be expected from this eroding coastline, although beach sand did cover much of the foreshore. However, we were able to see the main features of c.1.4m of Baventian clays at the base of the cliff and on the upper foreshore, including much bioturbation (including U-shaped ?*Arenicola* tubes) and some of the desiccation cracks interpreted as the drying out of sediments in the inter-tidal zone. Some of the very friable mollusc fauna was also found in the discontinuous shell seams, particularly *Macoma calcarea*. The mollusc fauna is listed and discussed by Long (1974). The macro- and micro-faunas both indicate cold water conditions and support the pollen evidence - the Boreal pollen assemblages indicate grass heath with sparse woodland, probably only able to grow in sheltered places. It may well have been the case that conditions were cold enough for sea-ice to have been present. The section is only 3km north of Easton Bavents, where the type section of the Baventian cold stage is displayed.

The overlying sands and gravels of the Westleton Beds, c.2m thick, are described and discussed in the classic paper by Hey (1967) and also by Mottram (1989), Mathers and Zalasiewicz (1996), Sinclair (1999) and many others in the recent literature. We discussed them at length and benefited greatly from Howard Mottram's detailed knowledge of the geology of these beds. It is thought that the Westleton Beds accumulated as a coastal shingle plain comparable to Dungeness today, or possibly in a tidal inlet and barrier island complex, in a temperate phase, possibly the Pastonian. The sedimentary structures were thus of great interest as evidence of environmental conditions and palaeogeography.

Above the Westleton Beds are c.4m of Kesgrave Formation (see above), the fluviatile deposits of the ancestral River Thames, which was not examined in detail.

"TWO ISLANDS" VISIT

Sunday 17th September

This was a joint meeting with the Essex Local Group of the Geologists' Association and the Essex Rock and Mineral Society to study two outcrops of the Coralline and Red Crags (reported by Banks in Society Newsletter No. 48). The number of easily accessible and well-exposed inland Crag pits is slowly decreasing as more and more become overgrown through neglect or disuse. These pits, two of the more frequented by Crag enthusiasts, display a number of interesting features.

Buckenay Farm, near Alderton

This "island" is an inlier of Red Crag, which forms a topographical high, surrounded by reclaimed Holocene salt marsh nearly 1km to the east of the former cliff line. The pit is described in Gibbard and Zalasiewicz (1988).

The Red Crag sediments show a number of structures. Most obvious are megaripples between 1 – 2 m high, but also channel bedded units and small and medium scale ripples. The ripples commonly show excellent examples of shell avalanche and imbrication structures. The foresets tend to be coarse and shelly sand, while bottomsets are often finer grained. Mud drapes can be seen in places, associated with small scale ripples and other silty partings.

The interpretation is of fairly shallow water, around 5 – 8m, with current directions generally towards the west-south-west, but very variable – between 225°-305°. Tidal current directions are superimposed upon this and also show much variation. Current velocities are estimated to have reached a maximum of about 0.8m/sec to have formed the ripples, when large sediment loads must have been transported, possibly during storms. The mud and silt partings were evidently deposited during quiet phases, when current velocities were much reduced – less than 0.1m/sec. It may be that these are the result of settling out of fine material during tidal cycles (Dixon, 1979; see for comparison Allen, 1982 or Visser, 1980).

The mollusc faunas predominantly represent shell gravels and the faunal composition does change – the % frequencies are given in Table 1. The lowest megaripple (set 1) of the north face contains a *Venerupis-Glycimeris* assemblage with significant frequencies of *Aloidis*, while the topmost ripple contains a *Spisula* shell gravel with a large frequency of *Mytilus*. Detailed sampling reveals that this vertical (i.e. temporal) change in assemblage type occurs from bottom to top throughout the pit and is accompanied by significant changes in other species, for example the increase in *Macoma spp, Mya* and *Cardium angustatum*; and the decrease in *Astarte spp*, *Venus ovata* and *Cardita corbis.*

Certain horizons, for example in the south face, are characterised by very numerous thin, irregular vertical endogenetic agglutinated tubes, up to 7cm long, occasionally composed of ovoid fecal pellets, possibly belonging to an amphipod or small worm; this trace fossil is also characteristic of parts of the upper Red Crag on a regional scale.

A similar sequence of structures and faunas is identifiable in the upper part of the Red Crag over much of the area between the Deben and Butley rivers and the vertical changes support the view (seen regionally) of a shallowing sea towards the close of Red Crag times.

Table 1. Percentage frequencies of key molluscan species at Buckenay Farm.

	North Set 1	**North Set 2**	**Centre Set 2**	**Centre Set 3**	**South Set 5**	**Centre Set 4**	**North Set 4**
Low shore epifauna							
Mytilus edulis	*5.3*	*9.5*	*9.5*	*9.2*	*12.9*	*10.7*	*8.2*
Total	6.1	10.1	10.1	10.0	13.1	11.1	9.3
Intertidal sandy shore							
Cerastoderma edule	*1.1*	*0*	-	*1.1*	*1.6*	*0*	*1.2*
Mya arenaria	*0*	*0*	*1.2*	*0*	*6.8*	*4.9*	*5.6*
Total	2.0	0	1.2	1.6	8.6	5.4	6.8
Sublittoral shell gravel							
Glycimeris glycimeris	*8.6*	*9.0*	*5.2*	*4.3*	*2.3*	*2.2*	*2.0*
Venerupis spp	*11.0*	*6.4*	*7.1*	*12.0*	*5.4*	*2.0*	*2.5*
Total	20.2	16.4	13.4	17.3	8.3	4.9	4.9
Sublittoral muddy sand							
Aloidis gibba	*11.8*	*8.8*	*7.6*	*8.7*	*3.5*	*3.2*	*1.9*
Total	13.1	9.2	8.0	9.2	4.0	3.8	2.2
Sublittoral clean sand							
Dosinia exoleta	*3.8*	*2.3*	*3.2*	*3.1*	*2.3*	*0*	*1.6*
Total	4.4	2.8	3.2	3.5	3.0	2.2	3.5
Sublittoral mud tolerant							
Turritella incrassata	*5.9*	*11.1*	*7.8*	*9.1*	*5.6*	*6.3*	*4.0*
Cyprina islandica	*0*	-	*0*	-	*0*	*0*	*0*
Total	6.2	11.1	8.3	9.1	5.8	6.5	4.6
Gravel/mud epifauna							
Buccinum undatum	*0*	*0*	-	-	*0*	*0*	*0*
Neptunea antiqua	-	-	-	-	*0*	*0*	*0*
Total	0	0	-	-	0	1.1	0
Various substrates							
Astarte digitaria	*1.2*	*1.2*	*1.0*	*0*	*0*	*0*	*0*
Chlamys opercularis	*1.1*	*0*	*0*	*0*	*0*	*0*	*1.6*
Venus ovata	*1.3*	*0*	*1.3*	*1.7*	*0*	*0*	*0*
Total	3.7	2.3	3.1	2.9	1.0	1.1	2.8
Extinct							
Nassarius reticosa	*0*	-	-	*0*	-	-	*0*
Natica hemiclausa	*0*	*0*	*0*	*0*	*0*	*0*	*1.3*
N. multipunctata	-	*0*	-	*0*	*0*	*0*	*0*
Nucella lapillus	-	*0*	-	-	*1.2*	*0*	*4.1*
Cardita corbis	*2.3*	*1.6*	*1.7*	*1.0*	*0*	*0*	*0*
Cardium angustatum	*0*	-	-	*0*	*4.1*	*4.7*	*2.4*
Macoma obliqua	*0*	*2.0*	*1.9*	*1.0*	*3.9*	*3.1*	*3.3*
M. praetenuis	*2.8*	*3.8*	*3.9*	*6.1*	*5.9*	*6.3*	*5.5*
Pholas cylindrical	*2.6*	*1.0*	*1.0*	*3.3*	*1.2*	*0*	*0*
Spisula spp	*8.9*	*17.4*	*17.5*	*9.9*	*15.6*	*27.4*	*22.6*
Total	31.8	36.3	37.1	34.6	42.9	52.8	50.6
Identified to genus only							
Natica	*0*	*0*	*0*	*0*	*0*	*1.7*	*3.3*
Astarte	*4.6*	*4.4*	*8.4*	*5.5*	*2.8*	*1.9*	*0*
Cardium	*1.8*	*0*	-	-	*2.7*	*1.3*	*4.5*
Total individuals	508	948	295	418	800	629	500
Total species	59	70	47	59	75	68	92
% of one individual	.20	.11	.34	.24	.13	.16	.07

Sutton Knoll

This locality (=Rockhall Wood of some authors) has been studied for over 160 years, long known as an island of Coralline Crag during Red Crag sea times, with its Coralline Crag cliffs and blocks 'buried' in Red Crag. The classic description was by Prestwich (1871), some of the figures of which were reproduced by Boswell (1928), but more recent descriptions have been by Balson and Long (1988) and Balson *et al.*, (1990); Wood (2000) reproduces two of Prestwich's diagrams and Balson *et al.*, (1993) describe the stratigraphy of the Coralline Crag as a whole.

The best Coralline Crag exposure is found on the northern side of the 'island'. The lower beds are shelly silty sands with evident bioturbation and an abundant fauna of molluscs, particularly bivalves, and bryozoans. Some horizons have been calcite-cemented to form a hard limestone. The upper horizons are shelly sands, from which aragonite has been removed by post-depositional solution processes to be re-precipitated as calcite cement to form a soft limestone (the "Bryozoan Rock Bed" of some authors, and often used as a building stone locally). Occasional solution pipes can be seen extending down from the surface. The sands exhibit well-developed cross-bedding and are interpreted as a tidal sand ridge in relatively shallow water migrating in a generally south-west direction.

The abutting and unconformable Red Crag is best seen on the east face of the 'island', but is much overgrown. It contains much derived Coralline Crag fauna, and even pebbles of that Crag encrusted with Red Crag barnacles, indicating that the Coralline Crag had already been cemented prior to the deposition of the Red Crag. Nevertheless, collecting yields an abundant fauna, including the little sea urchin *Echinocyamus pusillus*.

Notes for Table 1 (opposite)

Samples were taken from different ripple sets at faces in the north, central and southern parts of the pit, and numbered from the base upwards. All species were divided into 'ecologic groups' and the percentage totals are given for these as well. A frequency of '0' means >1%. The *Spisula spp.* are from the *S. ovalis-obtruncata-constricta* group, which may be 'ecophenotypes' of *S. solida* (Long 2000).

It was at Sutton Knoll that the ashes of Philip Cambridge were scattered by his widow and daughter in 1993. Philip was a leading and active member of the Geological Society of Norfolk for a great number of years, joining in 1965 and one time treasurer, field trip organiser, editor of the Bulletin, initiator of the Newsletter, and a renowned Crag enthusiast.

ACKNOWLEDGEMENT

Bob Markham is thanked for his time given freely and his detailed knowledge of the field sites described above.

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The Geological Society of Norfolk exists to promote the study and understanding of geology in East Anglia, and holds meetings throughout the year. For further details consult our Web Site (http://www.uea.ac.uk/env/gsn) or write to The Secretary, Geological Society of Norfolk, 8 Eaton Old Hall, Hurd Road, Eaton, Norwich, NR4 7BE.

Copies of the Bulletin (including older back copies – see p. 74 this issue) can be obtained from the editor at the address on p.1; it is issued free to members.

The illustration on the front cover is part of figure 2A from article 2 by Cobett in this issue of the Bulletin. It shows lithogenic drift facies classification from a transect at Flordon.

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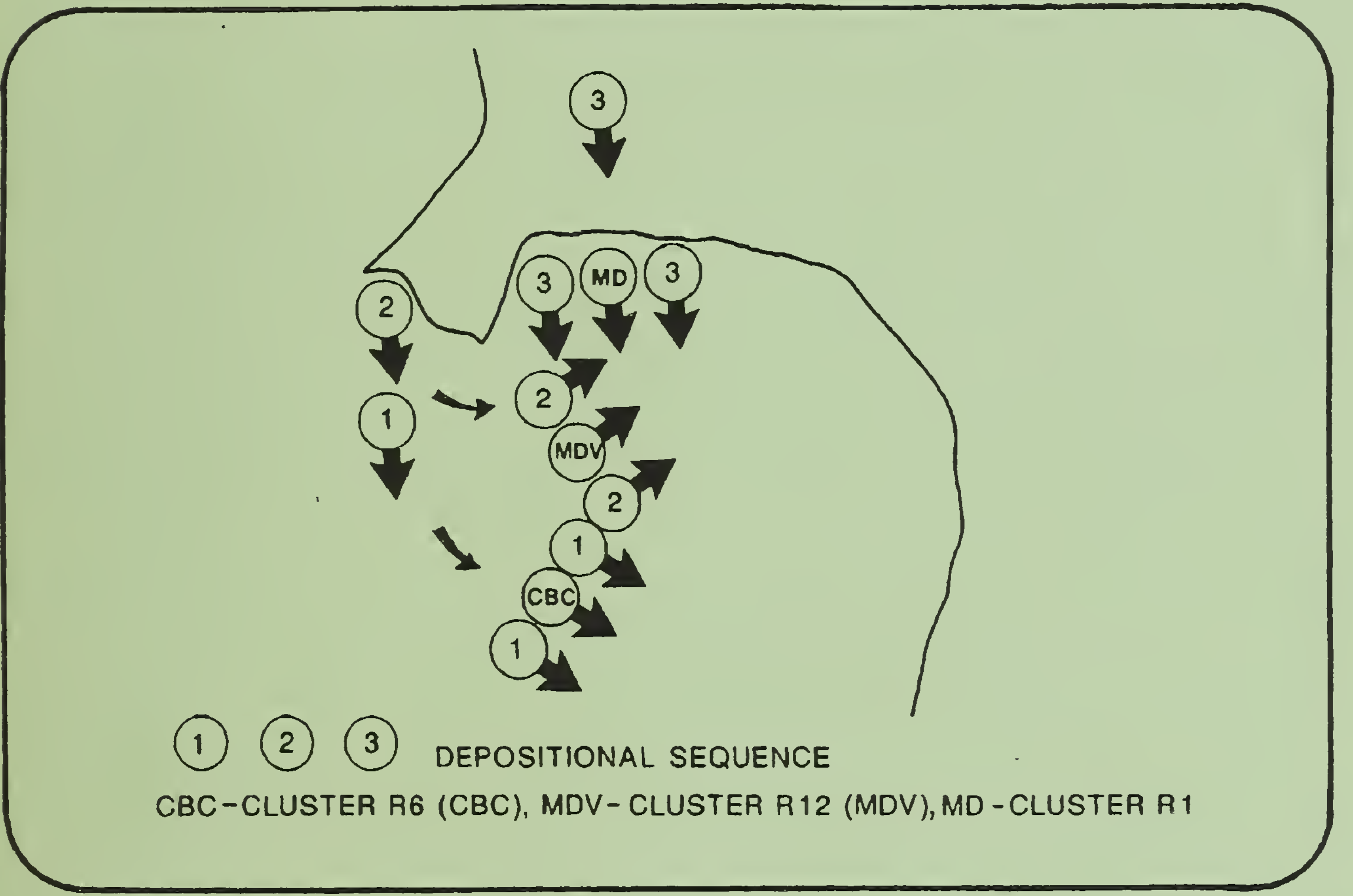
(FOR ARTICLES ON THE GEOLOGY OF EAST ANGLIA)

NO.52 2002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BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

No. 52 (2002) Published 2002

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EDITORIAL

Bulletin No. 52 contains two papers on the glacial sediments of East Anglia. The main contribution is from Dr William Corbett and discusses the genetic origin of the Lowestoft Till, based on mineral magnetic facies. In particular it analyses the potential sources of fine sand in the till. This paper builds on information in Dr Corbett's earlier papers published in Bulletin 51 (2001). The second contribution, authored by Dr Julian Andrews and others is a pilot study assessing the use of mineral magnetic parameters to distinguish between Devensian and Anglian glacial sediments in north Norfolk, a study initiated by the late Prof. Brian Funnell. Dr Corbett did the laboratory analysis for this second contribution and the data are thus directly comparable with those in the first article in this bulletin (52). We are very grateful to Mr Steve Booth of the British Geological Survey who encouraged us to finish off the study and for his subsequent collaboration. We hope that this pilot study will provoke further work in this area.

Bulletin 52 also contains a short note by Mr Paul Whittlesea on rare echinoid spines in the Norfolk Chalk and a brief report of society field meetings in 2000 authored by Dr Roger Dixon.

At the time of going to press there are a number of papers in review and other articles are in preparation by regular contributors to the Bulletin. This suggests that the future good health of the Bulletin is secure. As always, however, I encourage the continued submission of papers on all aspects of East Anglian geology, both from regular and new contributors.

BULLETIN INDEX 1986-2001

During the summer of 2001 the GSN decided to pay an undergraduate student from the University of East Anglia to update the index for the Bulletin. Miss Annika Swindell in the School of Environmental Sciences undertook this considerable task and the resulting index is included in the latter part of this Bulletin. The index covers Bulletins 36-51 (1986-2001), updating the first index which was published in 1986 (Bulletin 36). The job of indexing was both long and at times difficult; Annika Swindell spent much longer at this task than I had envisaged, and I thank her sincerely for the determination she showed in finishing it. The GSN is currently looking into the possibility of making the index available on the society website, which would greatly increase its accessibility.

GEOLOGICAL SOCIETY OF NORFOLK WEBSITE

The Geological Society of Norfolk has a website which can be reached at:

http://www.uea.ac.uk/env/gsn

Details of GSN activities can be found here including:

- Information on the aims and constitution
- Forthcoming meetings, lectures and fieldtrips
- Details of GSN projects
- Details of GSN publications, including instructions for authors
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INSTRUCTIONS TO AUTHORS

If possible, contributors should submit manuscripts as word-processor print out accompanied by a disk copy. We can handle most word-processing formats although MS Word, WordPerfect or ASCII files are preferred. In addition we accept typewritten copy and will consider legible handwritten material.

It is important that the style of the paper, in terms of overall format, capitalisation, punctuation etc. conforms as strictly as possible to that used in Vol. 52 of the Bulletin. Titles and first order headings should be capitalised, centred and in bold print. Second order headings should be centred, bold and lower case. Text should be 1½ line spaced. All measurements should be given in metric units.

References should be arranged alphabetically in the following style.

BALSON, P.S. & CAMERON, T.T.J. 1985. Quaternary mapping offshore East Anglia. *Modern Geology*, **9**, 221-239.

STEERS, J.A. 1960. Physiography and evolution: the physiography and evolution of Scolt Head Island. In: Steers, J.D. (ed.) *Scolt Head Island* (2nd ed.), 12-66, Heffer, Cambridge.

BLACK, R.M. 1988. *The Elements of Palaeontology*. 2nd Ed., Cambridge University Press, Cambridge. 404pp.

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The editors welcome original research papers, notes or comments, and review articles relevant to the geology of **East Anglia** as a whole, and do not restrict consideration to articles covering Norfolk alone. All papers are independently refereed by at least one reviewer.

ORIGIN OF THE CHALKY BOULDERCLAY (LOWESTOFT TILL) IN NORFOLK AND SUFFOLK BASED ON MINERAL MAGNETIC AND FACIES VARIATION

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ABSTRACT

This paper considers the genetic origin of the Chalky Boulderclay or Lowestoft Till in Norfolk and northern Suffolk based on the hypothesis that the mineral magnetic character of a glacial tills reflects its ice sheet source area and/or glacial transport pathway. This tests earlier reports that the mineralogical composition of the non-carbonate fine sand fraction was common to the Chalky Boulderclay and North Sea Drifts, derived from erosion of sediments from the present North Sea area. Statistical analysis of the mineral magnetic results show that fine sediment sources differentiate the 'North Sea Drift' and 'Lowestoft Till' groups. Ratio/Magnetism Variable-derived drift facies (R Variable drift facies) of the 'North Sea Drift' group are clearly associated with the Tertiary Yarmouth Road Beds outcropping on the floor of the North Sea, and characterised by low concentrations of goethite and haematite. In contrast, the 'Lowestoft Till' group is characterised by a narrower range of magnetic minerals but in higher concentration and dominated by varying proportions of magnetite. The source of this sand fraction could be in part the Shouldham Sands in west Norfolk and the Jurassic sandstones in east Yorkshire, but there is an additional magnetite component derived probably from igneous rock in northern England or eastern Scotland. The spatial pattern of R Variable drift facies shows that an equivalent of the 'North Sea Drift' group occurs in north Suffolk, whereas over most of the Chalky Boulder Clay plateau a Marly Drift (Lowestoft Till) facies occurs as a thick surface layer.

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INTRODUCTION

This paper is concerned primarily with the genetic origin of the Chalky Boulderclay or Lowestoft Till in Norfolk and northern Suffolk. The main theme is based on the hypothesis that the mineral magnetic character of a glacial till reflects the parent ice sheet source area and/or the transport pathway of the ice.

The primary data used in this study comes from more than 400 till samples collected from the subsurface of the Chalky Boulderclay plateau of Norfolk and Suffolk (Corbett 2001a; Fig. 1). Carbonate and non-carbonate particle size classes and magnetic properties of the non-carbonate fine sand fraction were the principal determinants (Corbett 2001a), and comparisons were made with selected reference samples of well characterised East Anglian tills (Corbett 2001a). Statistical analysis (Cluster Analysis) allowed facies recognition while Principal Component Analysis determined key or loaded differentiating variables (Corbett 2001a). Facies identified by Cluster Analysis from the data in the single percentage scale were referred to as the Measured Variable or M clusters and termed lithologic units. Facies recognised in the Ratio/Magnetism-derived percentage data were referred to as R clusters and termed lithogenic units (Corbett 2001a). Only the R Variable Cluster Analysis included the magnetic measurements.

The results of the two forms of Cluster Analysis were markedly different. The M clusters were clearly defined and easily matched to reference samples of the various East Anglian drifts. However, although the R clusters differentiated the major groupings of drifts - i.e. the North Sea Drift and Chalky Boulderclay - differentiation of individual facies within these groups was poor.

Mineral magnetics and the non carbonate sand fraction in glacial tills

The consistent presence of a non-carbonate sand fraction in the Lowestoft Till was noted by Perrin *et al.* (1973). They demonstrated a grain size mode of about 150 µm, and showed that the heavy minerals in the 63-105 µm fraction are qualitatively similar for both the Lowestoft Till and the North Sea Drift. They suggested that this sand came from the floor of the North Sea. As mineral magnetic analyses have been used to characterise till units elsewhere (Walden *et al.* 1987; 1992), it was hypothesised that mineralogical differences in the sand fraction might be identified from the remanent magnetism (see below), indicating the nature and origin of the fine sand itself, rather than the till as a whole. To examine this, samples

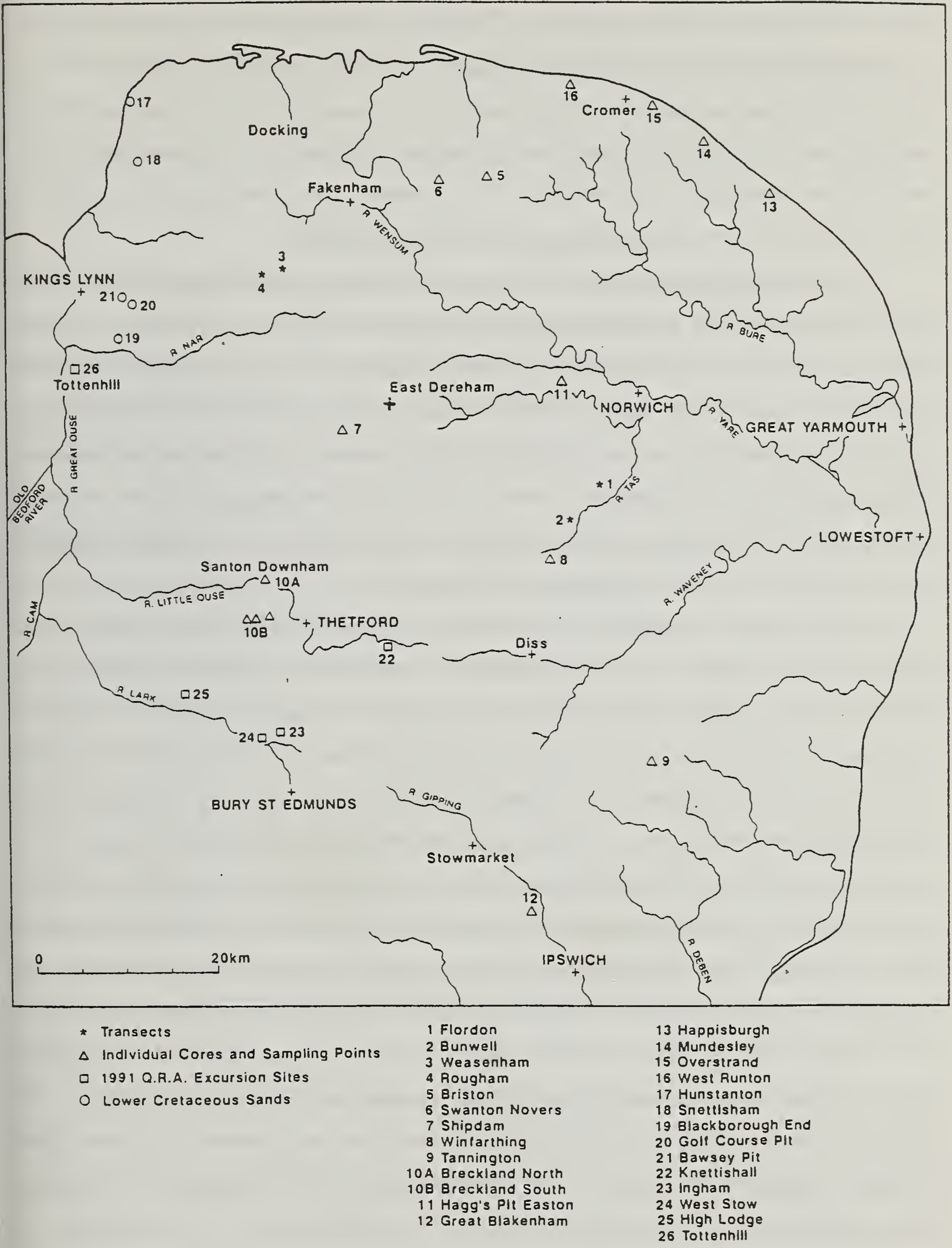

Fig. 1. Map of the main sampling locations.

were taken from sandy sediments and rocks that might have acted as source materials including: the Lower Cretaceous Carstone (CAR) and Leziate Sands (LEZ) of west Norfolk; the Tertiary Shouldham Sands (SHO.S) of west Norfolk; the Yarmouth Road Beds (YRB) of the North Sea Basin and Jurassic sandstones of the Scarborough (SCAR.F), Staithes (STA.F) and Cleveland (CLV.F) Formations of east Yorkshire. Coversands on the Breckland plateau were similarly sampled as possible sources of admixture to the underlying tills. Details of the localities and exact sample depths are given in Corbett (2001a).

Magnetic measurements were made on the non-carbonate fine sand fraction (see details in Corbett 2001a). Isothermal Remanent Magnetism (IRM) or more broadly magnetic remanence is a relative measure of the magnetism retained by the sample after it has been removed from a magnetic field of known strength. These relative measurements were converted to a standard scale using the 1000 mT remanence value (Saturation Isothermal Remanent Magnetism or SIRM) and made absolute by taking into account the weight of sample, standardizing this to a weight of 1 gram (Corbett 2001a). This value provided a measure of the concentration of magnetic mineral grains.

The magnetic properties of the samples were characterised in three ways. The absolute 1000 mT remanence value (A1000 mT) was used directly in the data analysis while the other two parameters were derived from magnetic remanence curves. Magnetic remanence curves (see e.g. Fig. 2), are produced by plotting various induced field strengths against their equivalent magnetic remanence value as %SIRM. The general shapes of these curves and the differences between them can be used to recognise and differentiate magnetic mineral composition. These differences were quantified in two ways. The Median Destructive Field (MDF) was derived by determining the field strength necessary to give a 50% remanence value, this being equal to the applied field which would overprint the "softest" 50% of the remanence. (The term "soft" here indicates remanence due to grains whose magnetic domains may be relatively easily re-ordered or overprinted when the sample is exposed to a new magnetic field). The MDF quantifies the magnetic character of the sample for the lower field strengths. The measurement used to characterize the upper field strengths is the difference between the remanence of the 300 mT and 1000 mT values, known as the "Hard" Isothermal Remanent Magnetism (HIRM).

Magnetic grain size is typically discussed in terms of 'domains'. Large crystals are known as multidomain grains and alignment of these domains reflect their response to external fields and their adjustment to each other. In contrast, with decreasing grain size, each grain forms its own single (magnetic) domain (see details in Corbett 1996).

Statistical tests of difference in this study were based on the Student 't' distribution at 99% confidence levels unless stated otherwise. Commonly used terms and abbreviations are defined in Table 1, and specific localities mentioned in the text are shown on Figure 1.

LITHOGENIC INTERPRETATION

Lithogenic differentiation of Measured Variable-derived drift facies

Table 2 shows the R Variable means and standard deviations for M Variable-derived clusters, while in Table 3 the M Variable-derived drift facies are ordered by the R Variable means of their loaded variables (excepting the MDF values). Differences in these ratios were intended to identify possible sediment source areas and directions of ice movement. For these reasons magnetic measurements on the fine sand fraction (see above) were included. Although the ordering of means in Table 3 are quite different from those based on M Variable means (Corbett 2001a, table 4), there is marked clustering of R Variable means into groups, clear breaks between groups and some consistency in the composition of groupings for the various key variables. The Student 't' test was used to evaluate critical differences in means between and within groupings of clusters for each key variable in Table 3. The results in Table 4 show that the most efficient discriminator between and within groupings of the major drifts is the fine sand fraction of non-carbonates (NC250R).

Since the likely sources of the non-carbonate fine sand fraction have been established (see above) their magnetic properties can be compared with those of the fine sand fraction in the major drift facies. MDF quantifies the magnetic character of samples at the lower field strengths and as such clearly differentiates 'soft' and 'hard' magnetism. The Student 't' test was used to compare the MDF means of the source sands with those of the major drift facies (Table 5).

The MDF means for the Carstone (CAR; Table 5) are markedly different to all the drift facies. However, other local fine sands (LEZ and YRB; Table 5) are not significantly different to Clusters M1 (NSD2), M3 (NSD1) and M6 (BR). In these facies either the Leziate Sands (LEZ) or Yarmouth Road Beds (YRB) could be major sand contributors, but in all the other clusters neither is. The Shouldham Sands (SHO.S), however, are not

Table 1. Terms, definitions and abbreviations used in this study (after Corbett 2001a)

Grain size, ratios, and mineral magnetic terms

TC	total carbonate
NC63	<63 µm non carbonate fraction
C63	<63 µm carbonate fraction
NC250	63-250 µm non carbonate fraction
NC250R	63-250 µm non carbonate fraction (R Variable form)
NCGT250	>250 µm non carbonate fraction
CGT500	>500 µm carbonate fraction
RFTOC	ratio of fine to coarse non carbonate NC250/NCGT250
CTOFINE	ratio of coarse to fine carbonate (CGT500/C63)
MDF	Median Destructive Field (50%)
MAGD	Magnetic Difference (1000 mT – 300 mT) [or HIRM]
HIRM	Hard Isothermal Remanent Magnetism
SIRM	Saturation Isothermal Remanent Magnetism
A 1000 mT	Absolute SIRM

Cluster terms (from Corbett 2001a)

M Variable-derived clusters

M1(NSD2) = North Sea Drift 2;
M2(GF) = Glaciofluvial;
M3(NSD1) = North Sea Drift 1;
M4(NSD3) = North Sea Drift 3;
M5(NSD/GF) = North Sea Drift/Glaciofluvial;
M6(BR) = Breckland Drift;
M7(CBC) = Chalky Boulderclay;
M8(MD) = Marly Drift;
M9(BRv) Breckland Drift variant;
M10(CBC/NSD) = Chalky Boulderclay/North Sea Drift;
M11&M15(MDv) = Marly Drift variants;
M12&M13&14(NSDv) = North Sea Drift variants;

R Variable-derived clusters

R1(MD) = Marly Drift;
R2(NSD) = North Sea Drift;
R3(BRv) = Breckland Drift variant;
R5(BR/NSD)= Breckland/North Sea; Drift
R6(CBC) = Chalky Boulderclay;
R10(CBCv) = Chalky Boulderclay variant
R12(MDv) = Marly Drift variant;
R4, R6-9, R11, R13-15(UC) = unclassified;

Table 2. Ratio means and standard deviations for Measured Variable derived clusters

CLUSTER NO	n	C >500R	C 500R	C 250R	C 63R	C CTOFINE	NC >500R	NC 500R	NC 250R	NC 63R	NC RFS	NC RFTOC	MDF	MAGG DIFF	A1000 mT
M1	25	0.043 ±0.029	0.011 ±0.008	0.046 ±0.035	0.900 ±0.054	0.049 ±0.035	0.092 ±0.059	0.154 ±0.042	0.397 ±0.084	0.358 ±0.090	0.397 ±0.084	1.864 ±0.859	59.2 ±15.0	9.0 ±6.6	32.9 ±18.4
M2	4	0.009 ±0.010	0.005 ±0.010	0.029 ±0.058	0.958 ±0.075	0.010 ±0.011	0.243 ±0.084	0.442 ±0.097	0.215 ±0.063	0.101 ±0.071	0.215 ±0.063	0.320 ±0.113	52.9 ±9.4	3.3 ±5.1	12.4 ±14.0
M3	14	0.034 ±0.054	0.024 ±0.032	0.027 ±0.036	0.844 ±0.268	0.051 ±0.090	0.072 ±0.027	0.132 ±0.034	0.353 ±0.034	0.443 ±0.083	0.353 ±0.094	1.895 ±0.901	57.7 ±10.9	9.0 ±4.6	34.5 ±19.6
M4	24	0.076 ±0.038	0.017 ±0.008	0.064 ±0.036	0.844 ±0.061	0.093 ±0.050	0.046 ±0.018	0.056 ±0.020	0.202 ±0.046	0.697 ±0.062	0.202 ±0.046	2.349 ±1.878	44.1 ±9.3	3.9 ±4.5	81.8 ±50.6
M5	9	0.166 ±0.140	0.024 ±0.013	0.119 ±0.093	0.691 ±0.201	0.314 ±0.316	0.214 ±0.049	0.359 ±0.058	0.376 ±0.050	0.052 ±0.041	0.376 ±0.050	0.665 ±0.133	51.3 ±3.9	0.2 ±5.5	88.1 ±61.5
M6	6	0.154 ±0.011	0.021 ±0.011	0.099 ±0.038	0.726 ±0.164	0.258 ±0.261	0.106 ±0.041	0.271 ±0.024	0.552 ±0.068	0.070 ±0.057	0.552 ±0.068	1.504 ±0.357	68.5 ±9.4	18.5 ±6.4	51.0 ±20.5
M7	103	0.103 ±0.034	0.019 ±0.006	0.048 ±0.009	0.830 ±0.009	0.126 ±0.049	0.055 ±0.036	0.070 ±0.039	0.164 ±0.058	0.711 ±0.118	0.164 ±0.058	1.434 ±0.319	48.9 ±12.3	9.7 ±8.2	53.0 ±24.8
M8	254	0.096 ±0.035	0.018 ±0.005	0.049 ±0.007	0.838 ±0.040	0.117 ±0.051	0.088 ±0.040	0.122 ±0.036	0.240 ±0.049	0.551 ±0.099	0.240 ±0.049	1.202 ±0.283	43.6 ±11.2	6.9 ±7.6	54.3 ±31.6
M9	2	0.169 ±0.048	0.018 ±0.003	0.046 ±0.000	0.766 ±0.046	0.223 ±0.076	0.532 ±0.087	0.128 ±0.053	0.174 ±0.042	0.166 ±0.008	0.174 ±0.042	0.266 ±0.077	33.2 ±4.8	-0.2 ±5.4	134.4 ±53.5
M10	11	0.078 ±0.029	0.018 ±0.007	0.042 ±0.010	0.862 ±0.042	0.092 ±0.035	0.040 ±0.018	0.055 ±0.019	0.180 ±0.084	0.725 ±0.094	0.180 ±0.084	2.206 ±2.115	45.6 ±8.6	4.7 ±5.8	63.2 ±26.5
M11	2	0.356 ±0.001	0.024 ±0.006	0.065 ±0.019	0.555 ±0.015	0.641 ±0.019	0.104 ±0.006	0.131 ±0.003	0.225 ±0.031	0.540 ±0.035	0.225 ±0.031	0.956 ±0.117	38.0 ±2.3	4.5 ±3.6	61.7 ±23.0
M12	1	0.000	0.000	0.000	0.000	0.000	0.055 ±0.000	0.311 ±0.000	0.326 ±0.000	0.309 ±0.000	0.326 ±0.000	0.891 ±0.000	66.7	20.2	20.0
M13	2	0.000	0.000	0.000	0.500 ±0.707	0.000	0.004 ±0.005	0.031 ±0.040	0.830 ±0.062	0.136 ±0.017	0.830 ±0.062	216.454 ±289.271	61.5 ±1.2	3.6 ±0.7	6.0 ±0.5
M14	1	0.000	0.000	0.000	1.000 ±0.000	0.000	0.061 ±0.000	0.115 ±0.000	0.627 ±0.000	0.197 ±0.000	0.627 ±0.000	3.567 ±0.000	56.9	-5.0	6.3
M15	11	0.016 ±0.013	0.007 ±0.003	0.021 ±0.003	0.956 ±0.017	0.017 ±0.015	0.128 ±0.048	0.141 ±0.036	0.261 ±0.061	0.471 ±0.109	0.261 ±0.061	0.997 ±0.219	28.7 ±6.0	5.0 ±10.5	66.6 ±23.5

Table 3. Measured Variable derived drift facies ordered by their loaded variable means in Ratio Variable form.

Cluster n	Ordered Lists of Clusters by Key Variable				
	C63R	**C>250R**	**NC250R**	**NC63R**	**MDF**
M1(NSD2) 25	NSDv 1.000 ±0.000	NSDv 0.000 ±0.000	CBC 0.164 ±0.058	CBC/ 0.725 NSD ±0.094	MDv 28.7 ±6.4
M2(GF) 4	GF 0.958 0.075	NSDv 0.000 ±0.000	BRv 0.174 ±0.042	CBC 0.711 ±0.118	BRv 33.2 ±4.8
M3(NSD1) 14	MDv 0.956 ±0.017	NSDv 0.000 ±0.000	CBC/ 0.180 NSD ±0.084	NSD3 0.697 ±0.062	MDv2 38.0 ±2.3
M4(NSD3) 24	NSD2 0.900 ±0.054	GF 0.013 ±0.018	NSD3 0.202 ±0.046	MD 0.551 ±0.099	MD 43.6 ±11.2
M5(NSD/GF)9	CBC/ 0.862 NSD ±0.042	MDv 0.023 ±0.015	GF 0.215 ±0.063	MDv2 0.540 ±0.035	NSD3 44.1 ±9.3
M6(BR) 6	NSD1 0.844 ±0.268	NSD2 0.054 ±0.033	MDv 0.225 2 ±0.031	MDv 0.471 ±0.109	CBC/ 45.6 NSD ±8.6
M7(CBC) 103	NSD3 0.844 ±0.061	NSD1 0.058 ±0.083	MD 0.240 ±0.049	NSD1 0.443 ±0.083	CBC 48.9 ±12.3
M8(MD) 254	MD 0.838 ±0.040	NSD3 0.093 ±0.044	MDv 0.261 ±0.061	NSD2 0.358 ±0.090	NSD/ 51.3 GF ± 3.9
M9(BRv) 2	CBC 0.830 ±0.039	CBC/ 0.095 NSD ±0.034	NSDv 0.326 ±0.000	NSDv 0.309 ±0.000	GF 52.9 ±9.4
M10 11 (CBC/NSD)	BRv 0.766 ±0.046	MD 0.114 ±0.038	NSD1 0.353 ±0.094	NSDv 0.197 ±0.000	NSDv 56.9 ±0.0
M11(MDv2) 2	BR 0.726 ±0.164	CBC 0.122 ±0.037	NSD/ 0.376 GF ±0.050	BRv 0.166 ±0.008	NSD1 57.7 ±10.9
M12(NSDv) 1	NSD/ 0.691 GF ±0.201	BR 0.175 ±0.136	NSD2 0.397 ±0.084	NSDv 0.136 ±0.017	NSD2 59.2 ±15.0
M13(NSDv) 2	MDv2 0.555 ±0.015	BRv 0.188 ±0.045	BR 0.552 ±0.068	GF 0.101 ±0.071	NSDv 61.5 ±1.2
M14(NSDv)1	NSDv 0.500 ±0.707	NSD/ 0.190 GF ±0.150	NSDv 0.627 ±0.000	BR 0.070 ±0.057	NSDv 66.7 ±0.0
M15(MDv) 11	NSDv 0.000 ±0.000	MDv2 0.380 ±0.005	NSDv 0.830 ±0.062	NSD/ 0.052 GF ±0.041	BR 68.5 ±9.4

significantly different from the drift facies of the 'Lowestoft Till' group of clusters which have, because of the low degree of freedom, very high critical 't' values. Neither are they significantly different from Cluster M4 (NSD3) or Cluster M5 (NSD/GF), although they do differ from the main representatives of the 'North Sea and Breckland drift' groups (Clusters M1 [NSD2], M3 [NSD1] and M6 [BR]). The picture for the Jurassic sandstones in less distinct. Although the Scarborough (SCAR.F), Staithes (STA.F) and most of the Cleveland (CLV.F) Formation MDF means differ from Cluster M6 (BR) and from two members of the 'Lowestoft Till' group (Clusters M8 (MD) andM15 (MDv)), they do not differ from Cluster M7 (CBC). The STA.F and CLV.F means differs from those of Clusters M1 (NSD2) and M3 (NSD1), but the SCAR.F mean is not different from the latter cluster. The CLV.F data does not differ from any of the drift facies but again this has, because of the low degrees of freedom, very high critical 't' values. The main point that emerges is that the Shouldham Sands are associated with the 'Lowestoft Till' group but not with the Breckland-North Sea Drifts. The link between the Scarborough Formation and Cluster M3 (NSD1) is difficult to explain. It could be related to the presence of Jurassic rocks on the floor of the North Sea in the area of the Sole Pit High.

MDF values are derived from magnetic remanence curves (Figs. 2A to D, data in Table 6). Figure 2A compares the remanence curves of local fine sand sources (CAR, LEZ and YRB). Apart from one atypical YRB sample the CAR envelope lies to the right of the YRB and LEZ envelopes which are effectively identical. The CAR plot and the single

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Table 3 (opposite)

Column headers and cluster abbreviations are defined in Table 1. Bold lines indicate breaks in cluster grouping continuity. ± values are 1 standard deviation; n = number of cases

Table footnote: To facilitate comparison between different variable sequences, the ordering of means, low to high or high to low is where necessary reversed. This arrangement identifies cluster sequences common to different variables, common subdivisions within these, and inconsistencies in both or either. The arrangement also provides an opportunity to assess, using the standard deviations, the significance of the difference in means between adjoining clusters.

Table 4. Significance (99%) of differences in Ratio Variable and Magnetism (MDF) means between major drift facies derived from Measured Variables.

C63R	**DF**	**CRIT 't'**	**CALC 't'**	**99% SIG**
MD/NSD2	27	2.77	5.80	√
MDv/NSD2	34	2.73	5.13	√
CBC/BR	5	4.03	1.53	X
CBC/NSD-GF	8	3.36	2.10	X
CGT250R				
MD/NSD1	13	3.01	2.32	X
MDv/NSD1	15	2.95	1.80	X
CBC/BR	5	4.03	1.05	X
CBC/NSD-GF	8	3.36	1.40	X
NC63R				
MD/CBC	162	2.62	11.95	√
MD/MDv	11	3.11	2.37	X
MD/NSD1	15	2.95	4.94	√
MDv/NSD2	16	2.92	2.91	X?
NC250R				
MD/CBC	163	2.62	11.95	√
MD/NSD1	13	3.01	4.53	√
NSD2/BR	8	3.36	4.58	√
MDF				
MD/MDv	256	2.62	20.44	√
MD/CBC	174	2.62	3.90	√
CBC/NSD2	3	5.84	3.15	X
CBC/NSD1	18	2.88	2.76	X
CBC/NSD3	44	2.69	2.18	X
CBC/BR	6	3.71	4.85	√
BR/NSD2	12	3.06	1.91	X
BR/NSD1	11	3.11	2.24	X
NSD2/NSD3	40	2.70	4.25	√

Drift facies abbreviations are defined in Table 1. DF = degrees of freedom.

atypical YRB sample indicate a much slower rate of magnetic acquisition and this is interpreted as dominance by 'hard' magnetic minerals such as haematite and goethite.

The remanence curves of the Shouldham Sands (Fig. 2B – mean of two samples) differ from the YRB envelope in having a marked central bulge which suggests a concentration of soft but single domain magnetite. Below the bulge the marked flattening of the curve at the lowest field strengths, indicates relative absence of 'soft' multi-domain magnetite. Above the bulge, the continued but more gradual rise indicates the presence of a 'hard' magnetic component. The second Shouldham Sands curve (Fig. 2B - from only one sample) shows clearly the variability of magnetic character in the SHO.S, being dominated by magnetically 'hard' minerals such as haematite and goethite.

The Scarborough Formation curve (Fig. 2C), lies to the left of the YRB envelope at lower field strengths and below 20mT has slightly more soft magnetism, i.e. magnetite. The Staithes and Cleveland Formations curve (Fig. 2D - based on six samples), shows some similarity to the SHO.S curve (Fig. 2B), having at lower field strengths, the same marked flattening and at middle field strengths, although less clearly marked, the single domain magnetite bulge. Two of the Cleveland Formation curves (Fig. 2D) show, at a lower concentration of minerals, the same characteristic shape. These curves, at the lower field strengths, indicate less multi-domain magnetite, while the curve, based on one sample (Fig. 2D), has a 'hard' magnetic character.

In summary, each of the sand sources considered in Figures 2A-D have varying distinguishing characters when compared with the YRB envelope. These differences that reflect variability in the mineral magnetic components, can now be compared to the magnetic character of the fine sand fraction in the M Variable-derived drift facies. In doing this two limitations are recognised: (1) that interpretations regarding particular magnetic minerals and their structural form can only be verified by more detailed magnetic measurements; and (2) where the magnetic character of the fine sand fraction in the M Variable-derived drift facies is the product of more than one source of sand, the recognition of the nature and contribution of individual components can only be resolved using mathematical mixing models.

Comparison of the YRB envelope with magnetic remanence curves of the major M Variable-derived drift facies (Figs. 3A and B) shows that most of the drift facies lack a

Table 5. Significance (99%) of differences in MDF means between possible sources of sand and major drift facies derived from Measured Variables.

	CASES	MDF MEANS	STANDARD DEVIATION
YRB	8	62.1	±5.63
LEZ	4	58.0	±2.85
CAR 1	11	594.7	±20.6
CAR 2	3	287.8	± 6.1
CAR 3	3	202.1	± 1.6
SHO.S	2	39.9	±3.5
SCAR.F	6	50.7	±1.2
STA-CLF.F	6	48.3	±1.5
CLF.F	2	71.3	±9.5
BRCS	7	61.5	±3.3

	DF	CRIT 't'	CALC 't'	DIFFERENCE AT 99% SIG.
LEZ/MDv	3	5.84	20.38	√
LEZ/MD	5	4.03	9.00	√
LEZ/CBC	9	3.25	4.81	√
LEZ/CBC-NSD	13	3.01	4.19	√
LEZ/NSD2	26	2.78	0.36	X
LEZ/NSD1	16	2.92	0.09	X
LEZ/NSD3	16	2.92	8.39	√
LEZ/NSD-GF	8	3.36	3.47	√
LEZ/BR	6	3.71	2.57	X
YRB/MDv	7	3.50	16.70	√
YRB/MD	9	3.25	8.72	√
YRB/CBC	13	3.01	5.62	√
YRB/CBC-NSD	17	2.90	5.05	√
YRB/NSD2	30	2.75	0.81	X
YRB/NSD1	20	2.84	1.25	X
YRB/NSD3	20	2.84	6.54	√
YRB/NSD-GF	12	3.06	4.54	√
YRB/BR	8	3.36	1.48	X
SHO.S/MDv	2-3	9.92-5.84	3.57	X
SHO.S/MD	1	63.66	1.44	X
SHO.S/CBC	1-2	63.66-9.92	3.27	X
SHO.S/CBC-NSD	4	4.60	1.59	X
SHO.S/NSD2	5-6	4.03-3.71	4.96	√
SHO.S/NSD1	5	4.03	4.66	√
SHO.S/NSD3	2-3	9.92-5.84	1.35	X
SHO.S/NSD-GF	1-2	63.66-9.92	4.08	X
SHO.S/BR	5	4.03	6.26	√

Table 5 (continued)

	DF	CRIT 't'	CALC 't'	DIFFERENCE AT 99% SIG.
SCAR.F/MDv	11	3.11	11.05	√
SCAR.F/MD	45	2.70	8.29	√
SCAR.F/CBC	89	2.66	1.38	X
SCAR.F/CBC-NSD	11	3.11	1.93	X
SCAR.F/NSD2	25	2.79	2.80	√
SCAR.F/NSD1	14	2.98	2.37	X
SCAR.F/NSD3	26	2.78	3.37	√
SCAR.F/NSD-GF	10	3.17	0.43	X
SCAR.F/BR	5	4.03	4.60	√
STA-CLV.F/MDv	12	3.06	9.68	√
STA-CLV.F/MD	27	2.77	5.04	√
STA-CLV.F/CBC	69	2.66	0.44	X
STA-CLV.F/CBC-NSD	11	3.11	1.01	X
STA-CLV.F/NSD2	26	2.78	3.56	√
STA-CLV.F/NSD1	14	2.98	3.16	√
STA-CLV.F/NSD3	27	2.77	2.11	X
STA-CLV.F/NSD-GF	11	3.11	2.09	X
STA-CLV.F/BR	5	4.03	5.20	√
CLV.F/MDv	1	63.66	6.10	X
CLV.F/MD	1	63.66	4.10	X
CLV.F/CBC	1	63.66	3.28	X
CLV.F/CBC-NSD	1	63.66	3.57	X
CLV.F/NSD2	1-2	63.66-9.92	1.65	X
CLV.F/NSD1	1-2	63.66-9.92	1.86	X
CLV.F/NSD3	1	63.66	3.90	X
CLV.F/NSD-GF	1	63.66	2.92	X
CLV.F/BR	2	9.92	0.36	X
BR.CS/BR	6	3.71	1.74	X

Where:

YRB	Yarmouth Road Beds
LEZ	Leziate Beds
CAR	Carstone
SHO.S	Shouldham Sands and Gravels
SCAR.F	Scarborough Formation
STA-CLV	Staithes-Cleveland Formations
CLV.F	Cleveland Formation
BR.CS	Breckland Coversand

DF = degrees of freedom.

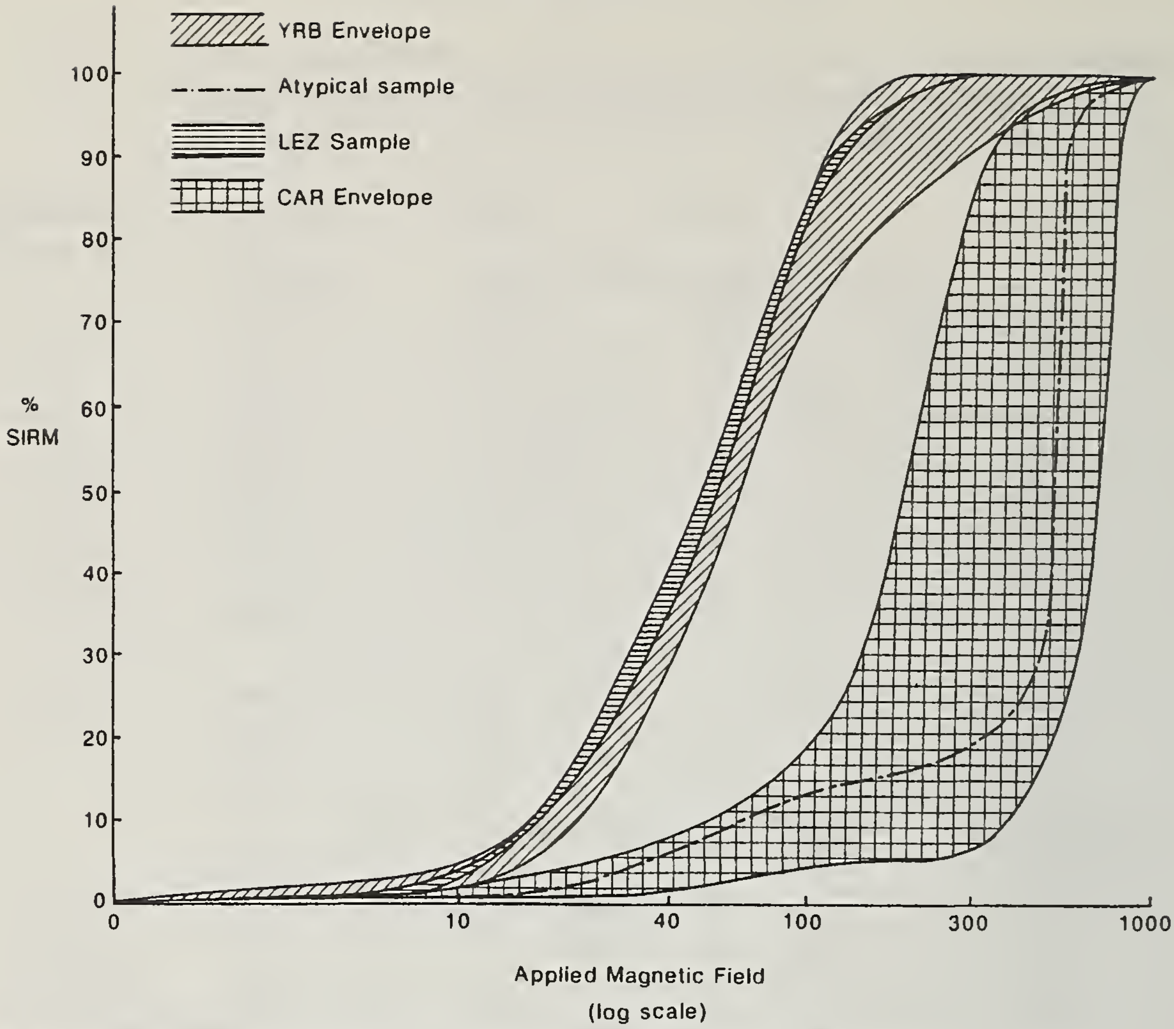


Fig. 2A. Magnetic remanence curves for the Yarmouth Road Beds, Carstone and Leziate Sands. The continuous lines enclosing envelopes define the range for each sand source while the broken line represents a single atypical YRB sample.

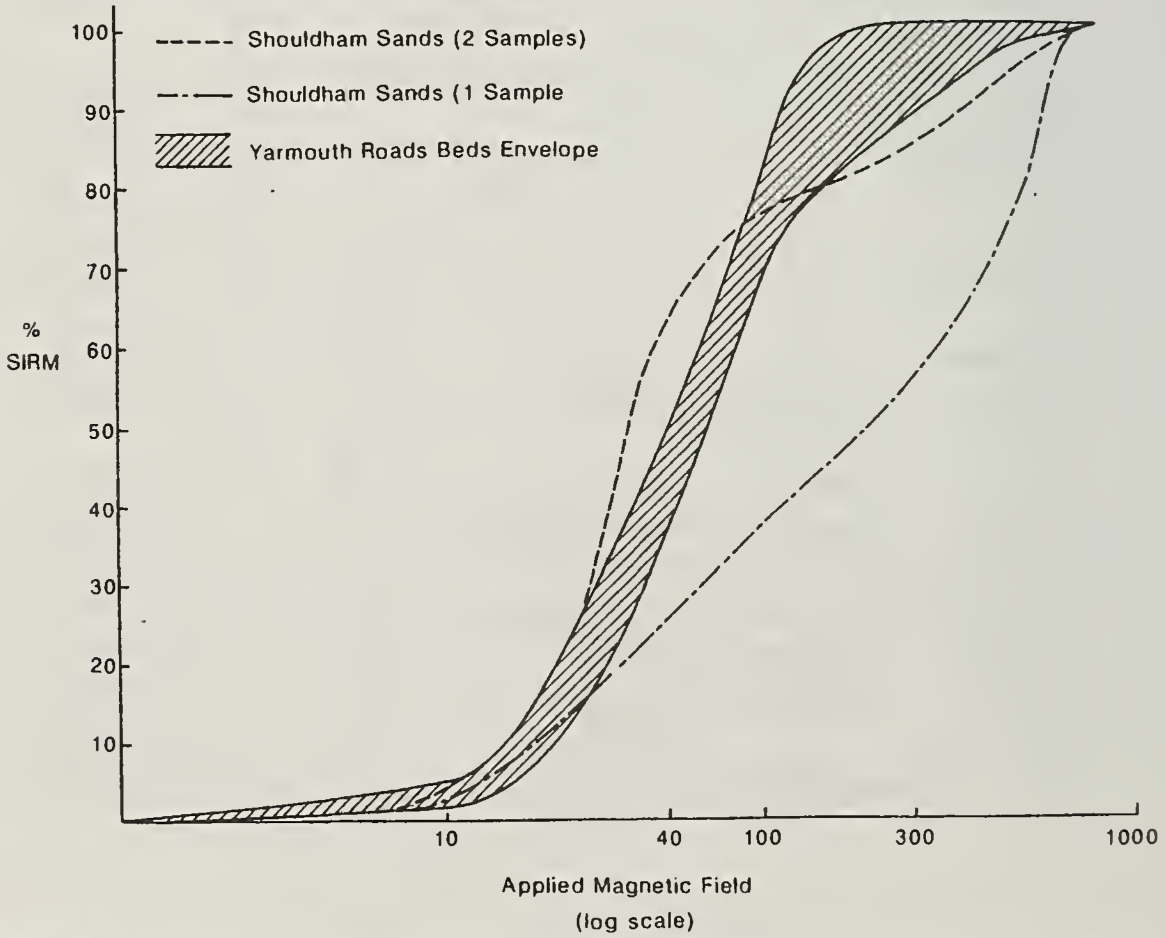


Fig. 2B. Magnetic remanence curves for the Yarmouth Road Beds and the Shouldham Sands.

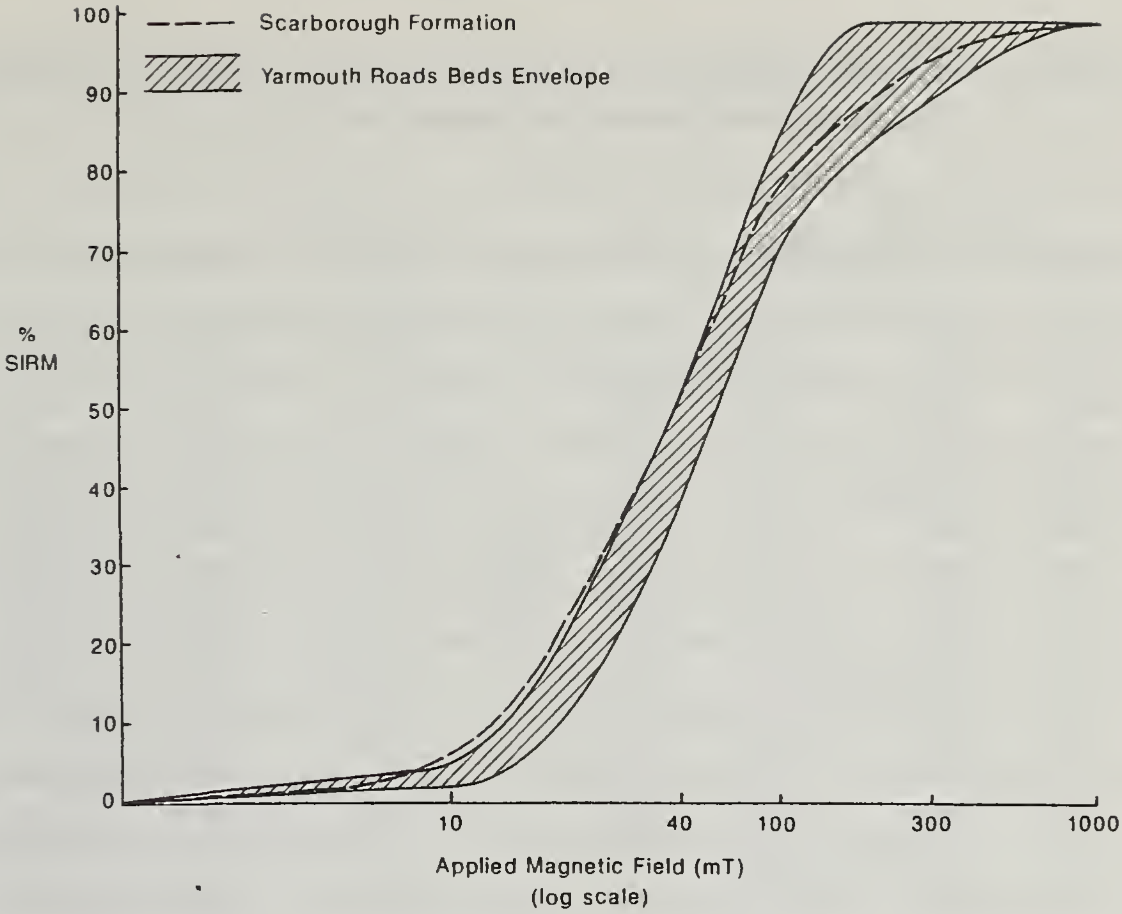


Fig. 2C. Magnetic remanence curves for the Yarmouth Road Beds and the Scarborough Formation.

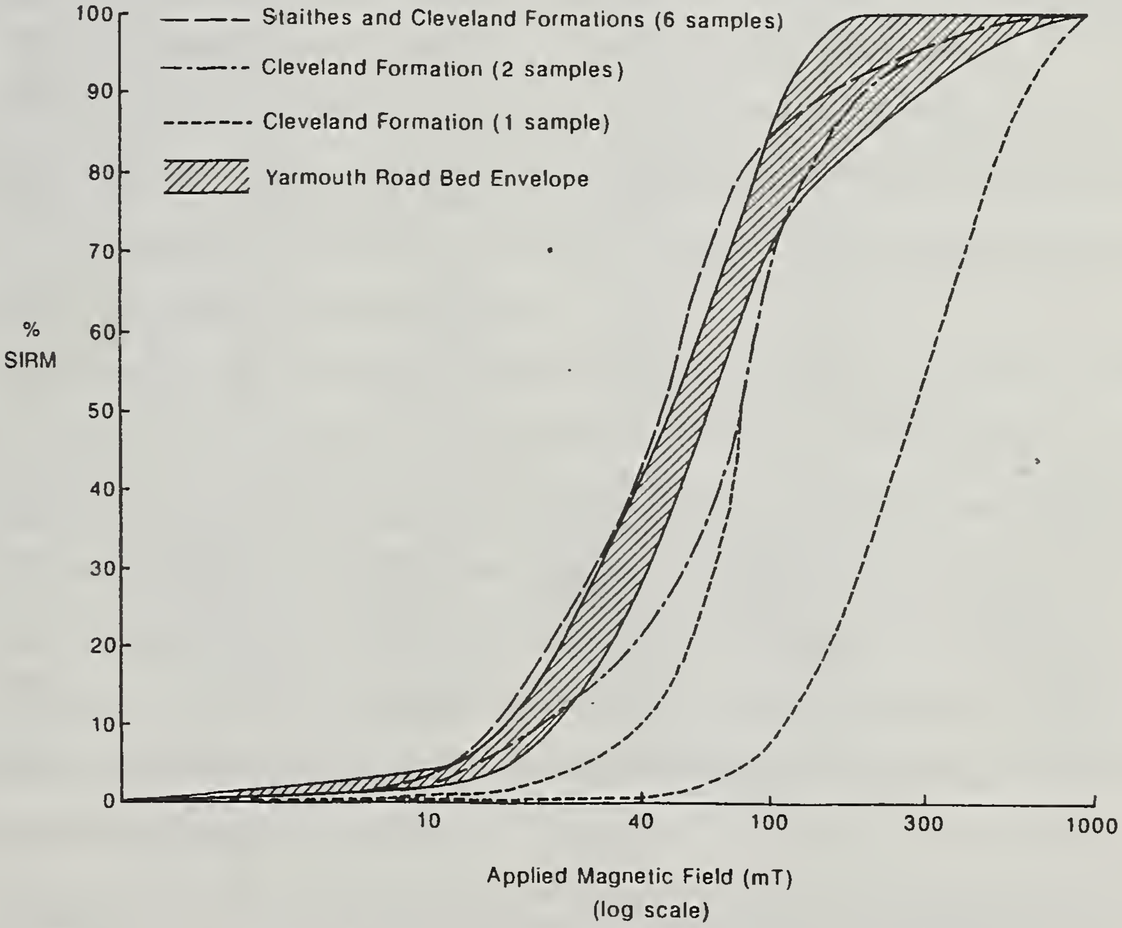


Fig. 2D. Magnetic remanence curves for the Yarmouth Road Beds and the Staithes and Cleveland Formations.

Table 6. Magnetic remanence means (milli Tesslas and Tesslas) for Measured Variable derived clusters and source sands

CLUSTER/FACIES		**10mT**	**40mT**	**50mT**	**100mT**	**300mT**	**1T**
M1	NSD2	5.7	38.3		72.3	91.0	100
M2	GF	8.4	41.9		79.5	95.7	99
M3	NSD	5.8	37.6		73.7	91.0	100
M4	NSD3	6.3	48.4		82.7	95.9	99.8
M5	NSD/GF	4.8	42.5		82.4	97.6	97.8
M6	BR	3.7	35.8	47.0	64.8	81.5	100
M7	CBC	5.7	46.7	46.0	78.0	90.0	99.8
M8	MD	9.3	50.2	62.4	81.0	92.6	99.5
M9	BRv	12.7	61.3		87.7	98.2	98.0
M10	CBC/NSD	4.7	46.9		83.9	94.8	99.5
M11	MDv2	9.8	53.2		86.3	95.6	100
M12	NSDv	6.1	39.8		62.7	79.8	100
M13	NSDv	3.0	36.2		74.7	96.4	100
M14	NSDv	3.7	39.7		76.2	100.0	95.0
M15	MDv1	25.1	65.3		81.5	92.5	97.6

	10mT	**40mT**	**100mT**	**300mT**	**1000mT**
YRB	4.4	41.3	84.2	100	98.9
	1.6	27.7	71.5	89.9	100
	0.8	6.5	13.8	17.9	100
LEZ	2.6	38.9	84.3	100	94.2
	2.1	34.0	80.7	100	96.6
CAR	0.2	1.2	12.7	51.2	100
	1.0	6.3	16.7	85.2	100
	2.0	8.2	15.3	20.4	100
	0.5	3.1	5.0	6.2	100
SHO.S1	2.3	21.9	37.5	57.2	100
SHO.S2	3.3±0.2	55.6±3.1	77.4±4.9	85.7±3.9	100
SCAR.F	6.1±2.9	40.2±0.9	78.4±3.3	95.8±0.9	100
STA-CLV.F	4.1±0.8	41.2±1.8	84.0±2.0	95.8±2.2	100
CLV.F1	2.0±1.4	21.5±3.2	67.9±9.0	96.3±0.4	100
CLV.F2	0.2	8.8	69.2	95.9	100
CLV.F3	0.2	0.8	7.2	54.0	100
BR.CS	3.4±0.5	37.4±1.6	64.1±1.9	78.6±2.5	100
BR.P.D	2.4±0.4	35.0±3.0	61.7±2.9	78.1±2.9	100

Drift facies and source sand abbreviations are given in Tables 1 and 5 respectively.

'hard' magnetic character. Cluster M6 (BR) is the exception and its plot at high magnetic field strength lies just within that of the CAR envelope. This feature is interpreted as a mixture of 'hard' and 'soft' magnetic minerals, the latter including the mineral magnetite. However, the curves of most of the drift facies fall either within the YRB envelope (Clusters M1 (NSD2), M3 (NSD1) and M5 (NSD/GF) (Fig. 3A)), or outside it (Clusters M8 (MD), M7 (CBC), M10 (CBC/NSD), M4 (NSD3), and particularly Cluster M12 (MDv) (Fig. 3B)). At lower magnetic field strengths these drifts lie outside the YRB envelope and well removed from the CAR data (cf. Fig. 2). Moreover, at lower field strengths the drift plots have a steep gradient, implying a faster rate of magnetisation with increasing field strength. This is a characteristic of 'soft' magnetic minerals and probably reflects the presence of magnetite. These data indicate either a non-local source of sand to the tills, or at least a marked contribution from such. Only the magnetic character of Cluster M6 (BR) suggests admixture with local fine sand sources, such as CAR or atypical YRB.

Comparison of the remanence curve envelope of the 'Lowestoft Till' group M Variable-derived drift facies with other possible sources of sand, including the Shouldham Sands, the Scarborough Formation and the Staithes and Cleveland Formations are shown in Figures 4A-C. Remanence curves for all of these potential sand sources fall outside the 'Lowestoft Till' group envelope at lower field strengths indicating lower amounts of 'soft' multi-domain magnetite. Although any of these sources **could** have contributed to the sand fraction in the 'Lowestoft Till' group of drifts, there is another **unsampled** source that provided the 'soft' multi-domain magnetism.

Drift samples from reference sites of the 'Lowestoft Till' group from Great Blakenham (Fig. 1), of the plateau Breckland Drifts and of the North Sea Drifts in north-east Norfolk, fit well into a classification of drift facies derived by Cluster Analysis of Measured Variables (Corbett 2001a). The key discriminating variables in this analysis (TC, NC63 and NC250) were similar to those used for drift definition in the past (e.g. Perrin *et al.* 1973; 1979). However, MDF is an additional discriminant variable that can be used to test the taxonomic fit, establish possible genetic inter-relationships and identify possible fine sand fraction sources to the drifts.

Comparison of the MDF means of M Variable-derived drift facies from the various reference sites using the Student 't' distribution suggests there is no significant difference

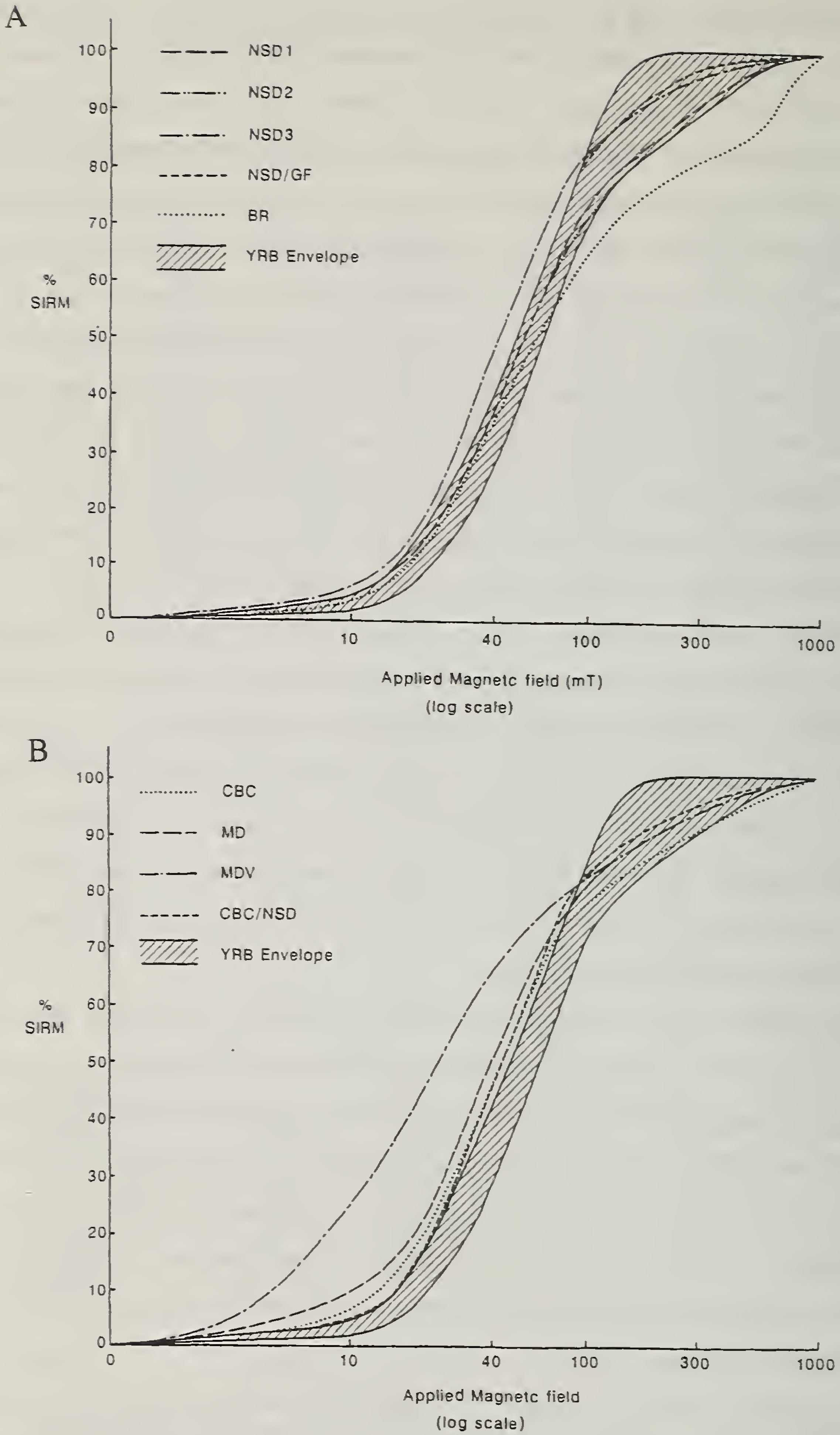


Fig. 3. Magnetic remanence curves for the Yarmouth Road Beds and M Variable derived drift facies of **A)** the North Sea and Breckland drifts and **B)** the Lowestoft Till group.

Table 7. Significance (99%) of differences in MDF means between major drift facies for reference sites.

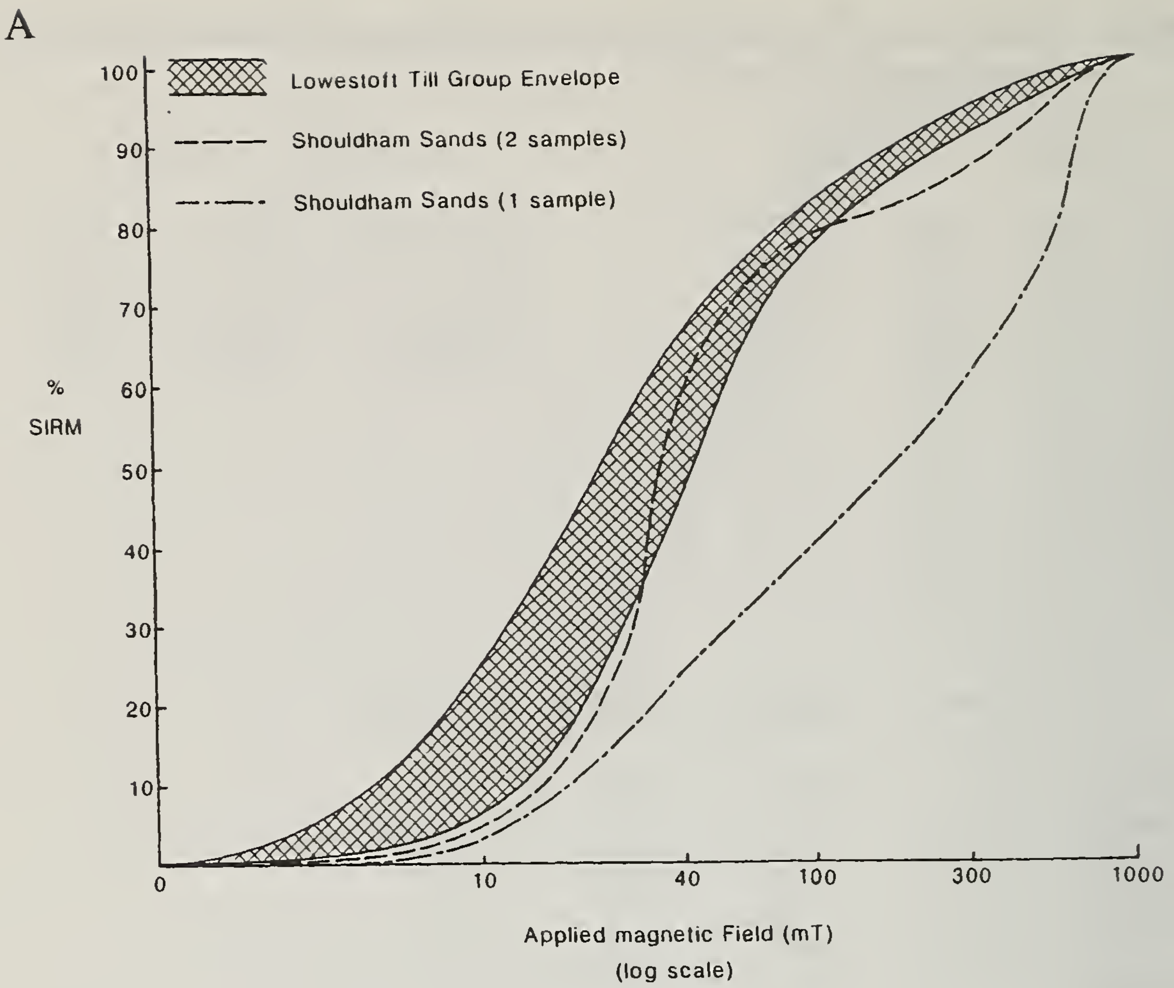
	CASES	MEANS	
YRB	8	62.1	±5.63
LEZ	4	58.0	±2.85
CAR 1	11	594.7	±20.6
CAR 2	3	287.8	±6.1
CAR 3	3	202.1	±1.6
SHO.S	2	39.9	±3.5
SCAR.F	6	50.7	±1.2
STA-CLV.F	6	48.3	±1.5
CLV.F	2	71.3	±9.5
BR.CS	7	61.5	±3.3

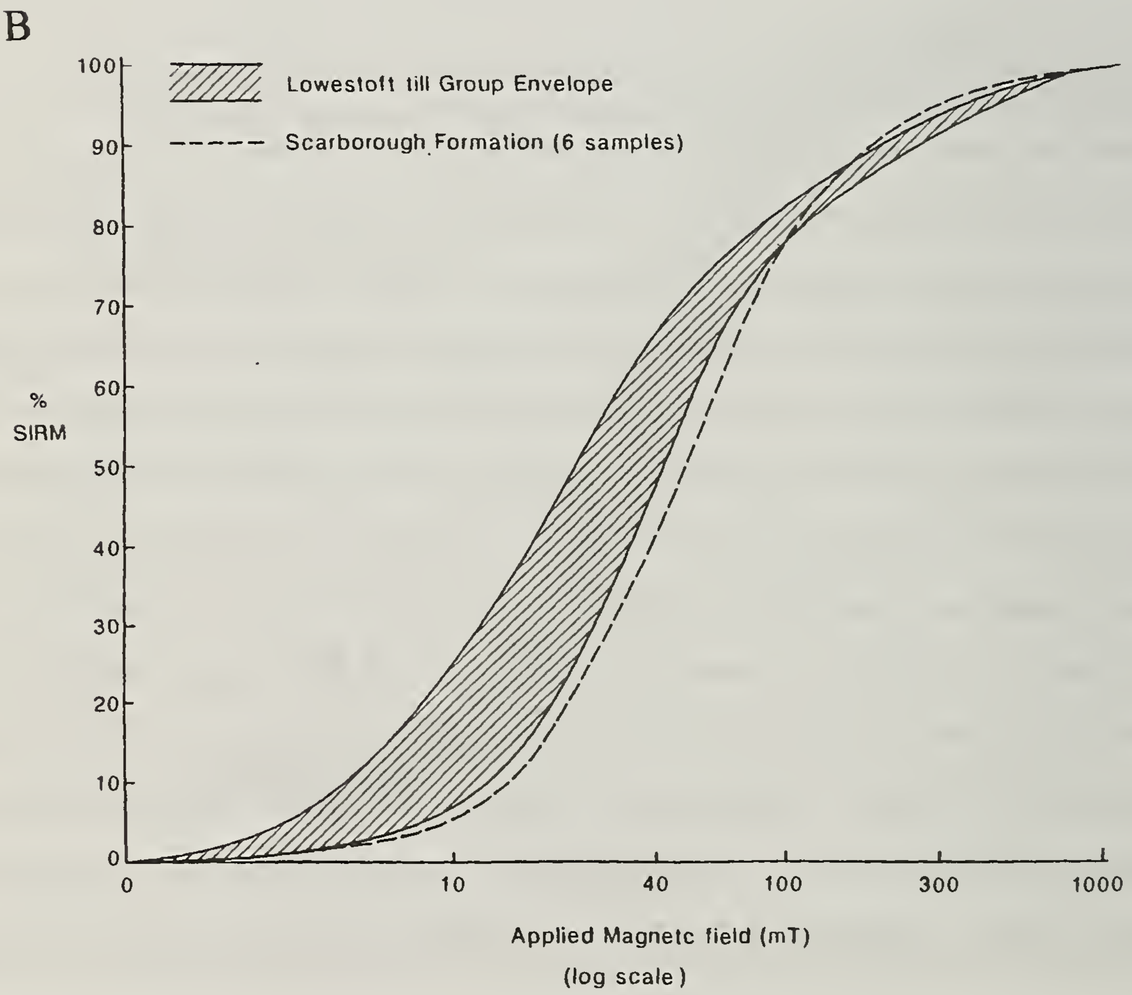
	CASES	MEANS	
CBC	6	66.43	±12.21
BR	5	70.38	±9.22
NSD1	4	76.48	±7.92
NSD2	2	75.72	±1.61

	DF	CRIT 't'	CALC 't'	99% SIG
CBC/BR	9	3.25	0.61	X
CBC/NSD2	8	3.36	1.58	X
CBC/NSD3	5	4.03	1.82	X
BR/NSD2	7	3.50	1.07	X
BR/NSD1	5	4.03	1.25	X
NSD2/NSD1	3	5.84	0.18	X

Drift facies and reference site abbreviations are given in Tables 1 and 5 respectively. ± values are 1 standard deviation; DF = degrees of freedom.

between any of the drift facies (Table 7). Note, however that this comparison is based on a small number reference samples. The data in Table 4 suggest that some cluster differentiation, at least within the 'Lowestoft Till' group, would be seen with more samples. Comparison of MDF means of the M Variable-derived drift reference sites with possible sources of fine sand are shown in Table 8. The only significant difference between the YRB or LEZ samples and reference drift samples is for Cluster M3 (NSD1). Also that the Shouldham Sands are significantly different from all the reference drift sites, possibly excepting Cluster M1 (NSD2). Cluster M7 (CBC) does not differ significantly from any of the Jurassic sandstones, and none of the drift facies differ significantly from the Cleveland Formation subset. Clearly, the fine sand fraction MDF means do not distinguish the traditionally defined drifts. The only positive result regarding sand source is the apparent link between Jurassic sandstones in Yorkshire and Cluster M7 (CBC).


A
Lowestoft Till Group Envelope
Shouldham Sands (2 samples)
Shouldham Sands (1 sample)
%
SIRM
100
90
80
70
60
50
40
30
20
10
0
10
40
100
300
1000
Applied magnetic Field (mT)
(log scale)


B
Lowestoft till Group Envelope
Scarborough Formation (6 samples)
%
SIRM
100
90
80
70
60
50
40
30
20
10
0
0
10
40
100
300
1000
Applied Magnetc field (mT)
(log scale)

C

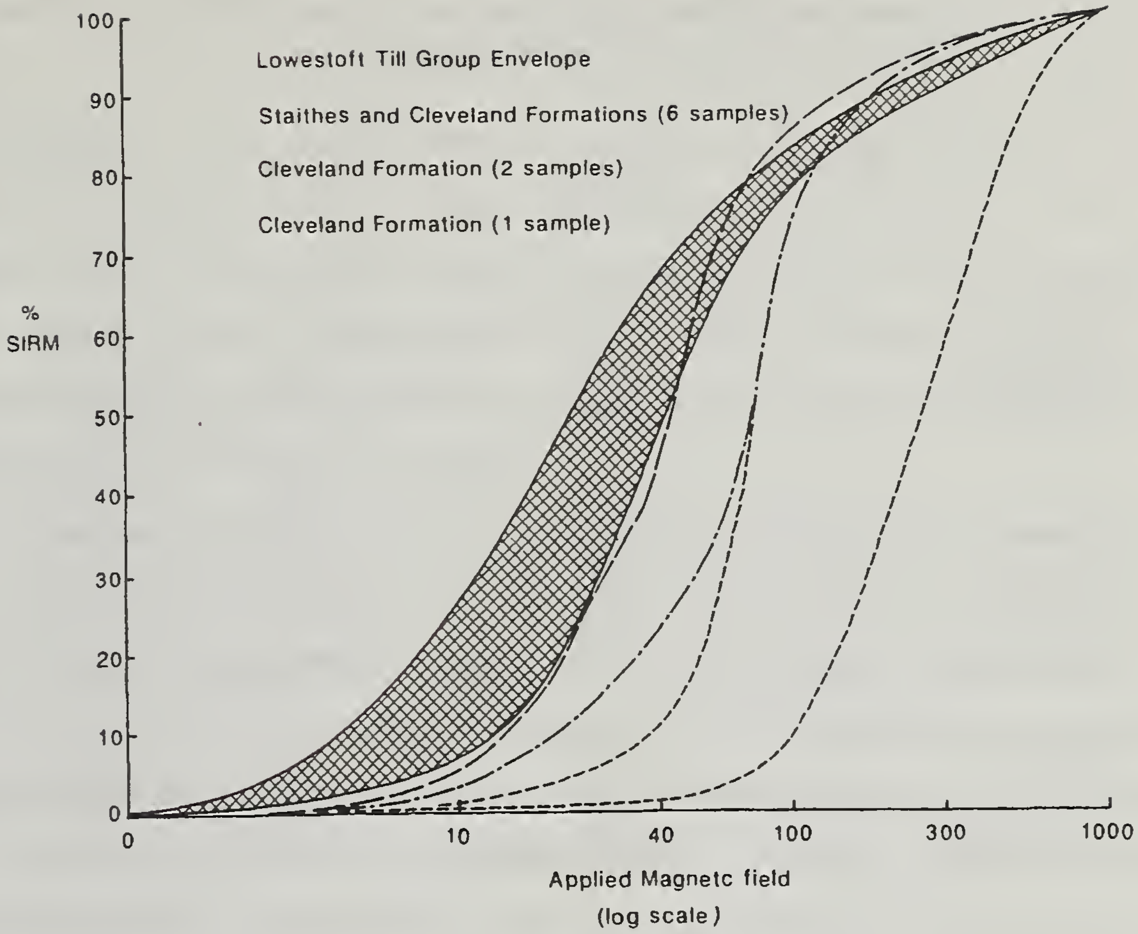


Fig. 4. Magnetic remanence curves for the Lowestoft Till group envelope (M Variables) and **A)** the Shouldham Sands; **B)** the Scarborough Formation and **C)** the Staithes and Cleveland Formations.

Lithogenic differentiation of Ratio/Magnetism-derived drift fàcies

Cluster Analysis using Ratio/Magnetism-derived variables produces a classification that may have an interpretative rather than descriptive basis (Corbett 2001a). The R cluster means and standard deviations are shown in Table 9 and ordered by the means of their loaded variables in Table 10. Three groupings of R-derived drift facies are recognized in Table 10. However, the first grouping (excepting Cluster R12 (MDv) in the MAGD sequence) contains only the minor drift facies. The second grouping contains all but one of the major drifts (Table 9) while the third grouping contains the major drift facies, Cluster R2 (NSD).

Table 8. Significance (99%) of difference in MDF means between sources of sand and major drift facies from reference sites.

	DF	CRIT 't'	CALC 't'	99% SIG
YRB/CBC	7	3.50	0.81	X
YRB/BR	6	3.71	1.81	X
YRB/NSD2	5	4.03	3.24	X
YRB/NSD1	7	3.50	5.94	√
LEZ/CBC	6	3.71	1.60	X
LEZ/BR	5	4.03	2.84	X
LEZ/NSD2	4	4.60	4.39	X
LEZ/NSD1	4	4.60	9.71	√
CAR3/NSD2	3	5.84	30.80	√
SHO.S/CBC	6	3.71	4.77	√
SHO.S/BR	5	4.03	6.35	√
SHO.S/NSD1	4	4.60	7.85	√
SHO.S/NSD2	1-2	63.66-9.92	13.16	?
SCAR.F/CBC	5	4.03	3.14	X
SCAR.F/BR	4	4.60	4.76	√
SCAR.F/NSD1	3	5.84	6.48	√
SCAR.F/NSD2	1-2	63.66-9.92	20.28	?
STA-CLV.F/CBC	5	4.03	3.61	X
STA-CLV.F/BR	4	4.60	5.31	√
STA-CLV.F/NSD1	3	5.84	7.06	√
STA-CLV.F/NSD2	1-2	63.66-9.92	21.30	?
CLV.F/CBC	2	9.92	0.59	X
CLV.F/BR	2	9.92	0.11	X
CLV.F/NSD1	2	9.92	0.67	X
CLV.F/NSD2	1	63.66	0.65	X
BR.CS/BR	4	4.60	2.07	X

Reference site abbreviations are defined in Table 5. DF = degrees of freedom.

Although the R Variables have high weightings in their Eigen Factors (part of the Principal Component Analysis, see Corbett 2001a), the difference in means of individual variables is typically very small, emphasising potential genetic similarity. This applies to almost all the C and NC ratios (Table 10). However, MDF and MAGD (Tables 10 and 11) do provide some statistical differentiation of the major drift facies. In relation to the ordered sequences of means in Table 10, MDF differentiates the major drifts (Table 11) and in particular splits up the grouping Cluster R1 (MD), Cluster R6 (CBC) and Cluster R12 (MDv), although it fails to differentiate Cluster R3 (BRv) from either Cluster R1 (MD) or R6 (CBC). MAGD partially separates the major drifts (Table 11) but does not distinguish between Clusters R1 (MD) and R6 (CBC).

Two general conclusions can be drawn from analysis of the R Variable-derived drift facies. Firstly, although the Eigen Factors derived from Principal Component Analysis of R Variables explain significant percentages of the overall variation (Corbett 2001a, table 9), their most heavily loaded individual variables, with one exception, do not differentiate the individual drift facies. Clearly in terms of the variables that describe gross lithology the major R-derived drift facies have much in common. Secondly, the MDF measurements of the fine sand fraction do differentiate most of the major drifts. As previously, for the M-derived clusters, this differentiation can now be related to possible sources of fine sand.

Differences in MDF means between possible fine sand sources and those of the major R-derived drifts were tested using the Student 't' distribution (Table 12). The Carstone (CAR) samples form three distinct MDF subsets and of these CAR3 (with the lowest mean) is compared to the major drift facies with the highest mean (Cluster R5 [BR/NSD]). In addition, the (Yarmouth Road Beds) YRB and Leziate Beds (LEZ) are compared to each other, while the Breckland coversands (BR.CS) are compared to Cluster R5 (BR/NSD) and to samples of the chalky drift on the Breckland Plateau (BR.P.D). Cluster R5 (BR/NSD) is also compared to the plateau drift.

The YRB and LEZ data differ significantly from all drift facies apart from Cluster R2 (NSD). The Shouldham Sands (SHO.S) do not differ significantly from any 'Lowestoft Till' group drift facies or from Cluster R3 (BRv) although with only one or two degrees of freedom, the critical 't' values are high. The SHO.S MDF data do, however, differ significantly from drift facies in the Breckland-North Sea Drift groups. The Jurassic

Table 9. Ratio/Magnetism derived drift facies ordered by cluster number and defined by their variable means in ratio form.

		CARBONATES					NON-CARBONATES						MAGNETISM		
Cluster No.	n	C >500R	C 500R	C 250R	C 63R	C CTOFINE	NC >500R	NC 500R	NC 250R	NC 63R	NC RFS	NC RFTOC	MDF	MAG DIFF	A1000mT
R1 (MD)	257	0.095 ±0.036	0.017 ±0.005	0.048 ±0.009	0.840 ±0.043	0.116 ±0.050	0.074 ±0.038	0.112 ±0.045	0.226 ±0.075	0.587 ±0.136	0.226 ±0.075	1.303 ±0.401	46.0 ±8.9	8.1 ±7.0	38.4 ±10.9
R2 (NSD)	21	0.028 ±0.047	0.015 ±0.026	0.041 ±0.054	0.916 ±0.111	0.038 ±0.075	0.120 ±0.102	0.202 ±0.153	0.335 ±0.132	0.342 ±0.248	0.335 ±0.132	2.072 ±2.278	57.5 ±10.9	6.1 ±6.7	22.5 ±15.2
R3 (BRv)	28	0.099 ±0.078	0.021 ±0.012	0.060 ±0.029	0.820 ±0.102	0.139 ±0.152	0.096 ±0.091	0.129 ±0.119	0.254 ±0.088	0.522 ±0.256	0.254 ±0.088	1.534 ±0.567	44.3 ±6.5	4.4 ±4.6	82.8 ±15.5
R4 (*UC)	1	0.343 ±0.000	0.028 ±0.000	0.231 ±0.000	0.399 ±0.000	0.860 ±0.000	0.210 ±0.000	0.387 ±0.000	0.329 ±0.000	0.734 ±0.000	0.329 ±0.000	0.551 ±0.000	50.3	-3.1	210.9
R5 (BR/NSD)	16	0.096 ±0.095	0.016 ±0.011	0.067 ±0.051	0.821 ±0.136	0.142 ±0.183	0.064 ±0.036	0.162 ±0.084	0.417 ±0.162	0.357 ±0.251	0.417 ±0.162	2.312 ±1.815	74.6 ±9.5	18.3 ±8.6	30.7 ±9.3
R6 (CBC)	102	0.094 ±0.056	0.018 ±0.007	0.045 ±0.011	0.843 ±0.066	0.118 ±0.095	0.093 ±0.052	0.106 ±0.047	0.224 ±0.067	0.578 ±0.142	0.224 ±0.067	1.252 ±0.368	41.7 ±10.8	5.9 ±7.4	72.5 ±12.1

Cluster and header abbreviation definitions are given in Table 1. ± values are 1 standard deviation; n =number of cases. (*UC) = unclassified.

Table 9 continued.

R7 (*UC)	2	0.093 ±0.024	0.022 ±0.004	0.190 ±0.161	0.695 ±0.180	0.143 ±0.071	0.123 ±0.127	0.211 ±0.217	0.236 ±0.078	0.430 ±0.422	0.236 ±0.078	1.240 ±1.041	49.2 ±3.7	-4.4 0.0	161.4 ±14.1
R8 (*UC)	1	0.049 ±0.000	0.011 ±0.000	0.055 ±0.000	0.885 ±0.000	0.056 ±0.000	0.070 ±0.000	0.122 ±0.000	0.213 ±0.000	0.596 ±0.000	0.213 ±0.000	1.109 ±0.000	132.9	43.4	43.2
R9 (*UC)	3	0.123 ±0.070	0.018 ±0.002	0.050 ±0.003	0.810 ±0.066	0.157 ±0.104	0.242 ±0.304	0.092 ±0.002	0.192 ±0.059	0.474 ±0.266	0.192 ±0.059	0.977 ±0.706	30.9 ±1.8	1.3 ±5.0	161.5 ±10.8
R10 (CBCv)	3	0.112 ±0.083	0.011 ±0.004	0.037 ±0.007	0.840 ±0.093	0.143 ±0.121	0.052 ±0.019	0.055 ±0.023	0.212 ±0.157	0.682 ±0.199	0.212 ±0.157	1.834 ±0.0606	86.9 ±3.5	22.7 ±15.4	88.8 ±4.2
R11 (*UC)	1	0.153 ±0.000	0.024 ±0.000	0.061 ±0.000	0.762 ±0.000	0.201 ±0.000	0.061 ±0.000	0.056 ±0.000	0.192 ±0.000	0.692 ±0.000	0.192 ±0.000	1.636 ±0.000	36.6	1.6	257.4
R12 (*UC)	21	0.093 ±0.035	0.020 ±0.006	0.051 ±0.010	0.836 ±0.045	0.114 ±0.048	0.106 ±0.049	0.112 ±0.039	0.249 ±0.061	0.533 ±0.121	0.249 ±0.061	1.206 ±0.294	34.6 ±6.4	2.4 ±3.2	115.1 ±12.8
R13 (*UC)	1	0.071 ±0.000	0.016 ±0.000	0.049 ±0.000	0.865 ±0.000	0.082 ±0.000	0.078 ±0.000	0.137 ±0.000	0.261 ±0.000	0.523 ±0.000	0.261 ±0.000	1.212 ±0.000	26.2	-4.2	239.7
R14 (*UC)	1	0.000 ±0.000	0.000 ±0.000	0.000 ±0.000	0.000 ±0.000	0.000 ±0.000	0.000 ±0.000	0.002 ±0.000	0.873 ±0.000	0.125 ±0.000	0.873 ±0.000	421.000 ±0.000	60.7	4.1	5.6
R15 (*UC)	1	0.008 ±0.000	0.005 ±0.000	0.020 ±0.000	0.968 ±0.000	0.008 ±0.000	0.080 ±0.000	0.154 ±0.000	0.239 ±0.000	0.527 ±0.000	0.239 ±0.000	1.024 ±0.000	17.8	5.0	276.2

Cluster No.	n	CGT250R		CTOFINE		C63R		NC63R	
R1 (MD)	257	R4	0.371 ±0.00	R4	0.860 ±0.00	R4	0.399 ±0.00	R11	0.692 ±0.00
R2 (NSD)	21	R11	0.177 ±0.00	R11	0.201 ±0.00	R7	0.695 ±0.18	R10 CBCV	0.685 ±0.20
R3 (BRV)	28	R9	0.140 ±0.07	R9	0.158 ±0.10	R11	0.762 ±0.00	R8	0.596 ±0.00
R4 (UC*)	1	R10 CBCV	0.123 ±0.09	R10 CBCV	0.143 ±0.12	R9	0.810 ±0.07	R1 MD	0.587 ±0.14
R5 (BR/NSD)	16	R3 BRV	0.121 ±0.08	R7	0.143 ±0.07	R3 BRV	0.820 ±0.10	R6 CBC	0.578 ±0.14
R6 (CBC)	102	R7	0.115 ±0.02	R5 BR/NSD	0.142 ±0.18	R5 BR/NSD	0.821 ±0.14	R12 MDV	0.533 ±0.12
R7 (UC*)	2	R12 MDV	0.113 ±0.04	R3 BRV	0.139 ±0.15	R12 MDV	0.836 ±0.04	R15	0.527 ±0.00
R8 (UC*)	1	R1 MD	0.112 ±0.04	R6 CBC	0.118 ±0.10	R1 MD	0.839 ±0.04	R13	0.523 ±0.00
R9 (UC*)	3	R5 BR/NSD	0.112 ±0.10	R1 MD	0.116 ±0.05	R10 CBCV	0.840 ±0.09	R3 BRV	0.522 ±0.26
R10 (CBCV)	3	R6 CBC	0.112 ±0.06	R12 MDV	0.114 ±0.05	R6 CBC	0.843 ±0.07	R9	0.474 ±0.27
R11 (UC*)	1	R13	0.087 ±0.00	R13	0.082 ±0.00	R13	0.864 ±0.00	R7	0.430 ±0.4
R12 (MDV)	21	R8	0.060 ±0.00	R8	0.056 ±0.00	R8	0.885 ±0.00	R5 BR/NSD	0.357 ±0.2
R13 (UC*)	1	R2	0.043 ±0.07	R2 NSD	0.038 ±0.07	R2 NSD	0.916 ±0.11	R2 NSD	0.34 ±0.2
R14 (UC*)	1	R15	0.012 ±0.00	R15	0.008 ±0.00	R15	0.968 ±0.00	R14	0.12 ±0.0
R15 (UC*)	1	R14	0.000 ±0.00	R14	0.000 ±0.00	R14	1.000 ±0.00	R4	0.07 ±0.0

Table 10. Ratio/Magnetism derived drift facies defined and ordered by their loaded variable means in ratio form. Column headers and cluster abbreviations as Table 1. Bold lines indicate breaks in cluster grouping continuity. ± values are 1 standard deviation; n = number of cases.

Table footnote: To facilitate comparison between different variable sequences, the ordering of means, low to high or high to low is where necessary reversed. This arrangement identifies cluster sequences common to different variables, common subdivisions within these, and inconsistencies in both or either. The arrangement also provides an opportunity to assess, using the standard deviations, the significance of the difference in means between adjoining clusters.

Table 10 (continued) **NCGT250R**		**RFOTC**		**MDF**		**MAGD**		**A1000mT**	
R14	0.002 ±0.00	R14	421.0 ±0.6	R15	17.8 ±0.0	R7	-4.4 ±0.6	R15	276.2 ±0.0
R10 CBCV	0.106 ±0.04	R5 BR/NSD	2.31 ±1.82	R13	2.62 ±0.0	R13	-4.2 ±0.0	R11	257.4 ±0.0
R11	0.117 ±0.00	R2 NSD	2.07 ±2.28	R9	30.9 ±1.8	R4	-3.1 ±0.00	R13	239 ±0.0
R1 MD	0.186 ±0.07	R10 CBCV	1.83 ±0.61	R12 MDV	34.6 ±6.4	R9	1.3 ±5.0	R4	210.9 ±0.0
R8	0.192 ±0.00	R11	1.64 ±0.0	R11	36.6 ±0.0	R11	1.6 ±0.0	R9	161.5 ±10.8
R6 CBC	0.198 ±0.09	R3 BRV	1.53 ±0.07	RR CBC	41.7 ±10.8	R12 MDV	2.4 ±3.2	R7	161.4 ±14.1
R13	0.216 ±0.00	R1 MD	1.30 ±0.40	R3 BRV	44.3 ±6.5	R14	4.1 ±0.0	R12 MDV	115.1 ±12.8
R12 MDV	0.218 ±0.07	R6 CBC	1.25 ±0.37	R1 MD	46.0 ±8.9	R3 BRV	4.4 ±4.6	R10 CBCV	88.8 ±4.2
R3 BRV	0.224 ±0.19	R7	1.24 ±1.04	R7	49.2 ±3.7	R15	5.0 ±0.0	R3 BRV	82.8 ±15.5
R5 BR/NSD	0.226 ±0.11	R12 MDV	1.21 ±0.29	R4	50.3 ±0.0	R6 CBC	5.9 ±7.5	R6 CBC	72.5 ±12.1
R15	0.234 ±0.00	R13	1.21 ±0.00	R2 NSD	57.5 ±10.9	R2 NSD	6.1 ±6.7	R8	43.2 ±0.0
R2 NSD	0.323 ±0.24	R8	1.11 ±0.00	R14	60.7 ±0.0	R1 MD	8.1 ±7.1	R1 MD	38.4 ±10.9
R7	0.334 ±0.34	R15	1.02 ±0.00	R5 BR/NSD	74.6 ±9.5	R5 BR/NSD	18.3 ±8.6	R5 BR/NSD	30.7 ±9.3
R9	0.334 ±0.30	R9	0.98 ±0.71	R10 CBCV	86.9 ±3.5	R10 CBCV	22.7 ±15.4	R2 NSD	22.5 ±15.2
R4	0.597 ±0.00	R4	0.55 ±0.00	R8	132.9 ±0.0	R8	43.4 ±0.0	R14	5.6 ±0.0

sandstones (SCAR.F and STA-CLV.F) differ significantly from most of the drift facies, excepting Clusters R2 (NSD) and R1 (MD). The CLV.F subset does not differ from any of the drift facies but again, with only one degree of freedom, the critical 't' values are very high. The Breckland coversand (BR.CS) differs significantly from Cluster R5 (BR/NSD) but not from the plateau drift (BR.P.D) at 99% confidence levels, although at 95% confidence the latter differences are significant. There is no significant difference between the YRB and LEZ data, and the CAR 3 (see above) subset is significantly different to Cluster R5 (BR/NSD), the drift facies with the highest MDF mean.

Table 11. Significance of differences in means in Ratio and Magnetism variables between major drift facies derived from Ratio/Magnetism variables.

FACIES	CASES	RFTOC		MDF		MAGD	
MDv	21	1.21	±0.29	34.6	±6.4	2.4	±3.2
MD	257	1.30	±0.40	46.0	±8.9	8.1	±7.1
CBC	102	1.25	±0.37	41.7	±10.8	5.9	±7.5
BRv	28	1.53	±0.57	44.3	±6.5	4.4	±4.6
BR/NSD	16	2.31	±1.82	74.6	±9.5	18.3	±8.6
NSD	21	2.07	±2.28	57.5	±10.9	6.1	±6.7

RFTOC

	DF	CRIT 't'	CALC 't'	99% SIG
MD/MDv	27	2.77	1.32	X
MD/CBC	200	2.62	1.13	X
MD/BRv	30	2.75	2.08	X
MD/NSD	20	2.84	1.55	X
MD/BR-NSD	15	2.95	2.22	X
CBC/MDv	35	2.73	0.55	X
CBC/BR-NSD	15	2.95	2.32	X
CBC/NSD	20	2.84	1.64	X
NSD/BRv	22	2.82	1.06	X
NSD/BR-NSD	35	2.73	0.36	X
MDv/BR-NSD	16	2.92	2.39	X
MDF				
MD/MDv	12	3.06	7.59	√
MD/CBC	159	2.62	3.57	√
MD/BRv	39	2.70	1.26	X
MD/NSD	22	2.82	4.71	√
CBC/MDv	47	2.68	4.04	√
CBC/BRv	72	2.65	1.60	X
NSD/BR-NSD	34	2.73	5.09	√
MAGD				
MD/MDv	39	2.70	6.89	√
MD/CBC	177	2.62	2.54	X
MD/BRv	42	2.69	3.79	√
MD/BR-NSD	16	2.92	4.65	√
MD/NSD	24	2.80	1.31	X
CBC/MDv	72	2.65	3.43	√
CBC/BRv	71	2.65	1.31	X
CBC/NSD	31	2.74	0.12	X
NSD/BRv	34	2.73	1.00	X
NSD/BR-NSD	28	2.76	4.69	√
NSD/MDv	29	2.76	8.30	√

Drift facies abbreviations are defined in Table 1. ± values are 1 standard deviation
DF = degrees of freedom.

The conclusions from these comparisons between R-derived data are: (1) that neither the YRB nor the LEZ contribute significantly to the fine sand fractions of the drifts; (2) that for Cluster R2 (NSD), either the YRB or the LEZ could be the fine sand source; (3) that the Shouldham Sands could have contributed significantly to the fine sand fraction in the 'Lowestoft Till' group (Clusters R1 (MD), R6 (CBC) and R12 (MDv)); and (4) that for the Jurassic sandstones, the only relevant link is between the STA-CLV.F and Cluster R1 (MD) - excluding the Cleveland Formation subset that has just two samples.

As the MDF values are derived from magnetic remanence curves, comparison of the plots of the major drift facies with those of the potential sand sources refines the interpretation. The YRB envelope is compared to the remanence curves of the R-derived drift facies in Figure 5 (data in Table 13), and the 'Lowestoft Till' group envelope is compared to remanence curves of the SHO.S (Fig. 6A), SCAR.F (Fig. 6B), and STA-CLV.F (Fig. 6C). As when considering the M Variable-derived data, few of the major drifts in Figure 5, have the 'hard' magnetic characteristics of haematite and goethite seen in the Carstone (cf. Fig. 2A). The exception, again at high field strengths and again indicating a mixture of 'hard' and 'soft' minerals, is Cluster R5 (BR/NSD). Further similarities with the M Variable derived data are that Cluster R2 (NSD) is almost entirely within the YRB envelope (Fig. 5). As indicated earlier, at lower field strengths the drift plots have steeper curves indicative of 'soft' magnetic minerals like magnetite. This characteristic is clearest in Cluster 12 (MDv), but progressively less clear in Clusters R6 (CBC), R3 (BRv) and R1 (MD). As for the M Variable-derived data, this characteristic is not a feature of local fine sand sources. The feature common to the SHO.S (Fig. 6A), SCAR.F (Fig. 6B), and STA-CLV.F (Fig. 6C) remanence curves is that at lower field strengths, they all lie to the right of the 'Lowestoft Till' group envelope, lacking the 'soft' multi-domain magnetism component of the 'Lowestoft Till' group.

Two general points emerge. Firstly, with regard to the 'Lowestoft Till' group of drift facies, although the Shouldham Sands and the Jurassic sandstones, could have contributed to their fine sand fraction, their soft, multi-domain component is definitely derived from some other source. Secondly, it is clear that the YRB and LEZ sands are magnetically indistinguishable (Table 12). This is surprising since the Leziate Sands (LEZ) are a distinctive white quartz sand, pure enough to be used for glass making.

Table 12. Significant (99%) differences in MDF means between sand sources and major drift facies derived from Ratio/Magnetism Variables

	CASES	MEANS			CASES	MEANS	
YRB	8	62.1	±5.6	MDv	21	34.6	±6.4
LEZ	4	58.0	±2.9	MD	257	46.0	±8.9
CAR 1	11	594.7	±20.6	CBC	102	41.7	±10.8
CAR 2	3	287.8	±6.1	BRv	28	44.3	±6.5
CAR 3	3	202.1	±1.6	BR-NSD	16	74.6	±9.5
SHO.S	2	39.9	±3.5	NSD	21	57.5	±10.9
SCAR.F	6	50.7	±1.2	BR.PD	4	73.8	±6.1
STA-CLV.F	6	48.3	±1.5				
CLV.F	2	71.3	±9.5				
BR.CS	7	61.5	±3.3				

	DF	CRIT 't'	CALC 't'	99% SIG
YRB/MDv	15	2.95	11.3	√
YRB/MD	8	3.36	7.83	√
YRB/CBC	12	3.06	9.07	√
YRB/BRv	13	3.01	7.04	√
YRB/BR-NSD	21	2.83	4.04	√
YRB/NSD	24	2.8O	1.49	X
LEZ/MDv	10	3.17	11.63	√
LEZ/MD	4	4.60	7.73	√
LEZ/CBC	7	3.50	9.06	√
LEZ/BRv	8	3.36	7.21	√
LEZ/BR-NSD	17	2.90	5.97	√
LEZ/NSD	20	2.84	0.18	X
YRB/LEZ	10	3.17	1.67	X
CAR/BR-NSD	17	2.90	50.05	√
SHO.S/MDv	2	9.92	1.87	X
SHO.S/MD	1	63.66	2.41	X
SHO.S/CBC	1-2	9.92-63.66	0.66	X
SHO.S/BRv	1-2	9.92-63.66	1.59	X
SHO.S/BR-NSD	4	4.60	10.12	√
SHO.S/NSD	4	4.60	5.13	√
SCAR.F/MDv	24	2.80	10.88	√
SCAR.F/MD	24	2.80	6.35	√
SCAR.F/CBC	77	2.66	7.65	√
SCAR.F/BRv	32	2.75	4.84	√
SCAR.F/BR-NSD	16	2.92	9.86	√
SCAR.F/NSD	22	2.82	2.80	X

Table 12 (Continued)

	DF	CRIT 't'	CALC 't'	99% SIG
STA-CLV.F/MDv	25	2.79	8.98	√
STA-CLV.F/MD	16	2.92	2.78	X
STA-CLV.F/CBC	56	2.66	5.36	√
STA-CLV.F/BRv	32	2.75	2.91	√
STA-CLV.F/BR-NSD	17	2.90	10.72	√
STA-CLV.F/NSD	22	2.82	3.75	√
CLV.F/MDv	1	63.66	5.35	X
CLV.F/MD	1	63.66	3.75	X
CLV.F/CBC	1	63.66	4.35	X
CLV.F/BRv	1	63.66	3.95	X
CLV.F/BR-NSD	1	63.66	0.46	X
CLV.F/NSD	1	63.66	1.94	X
BR.CS/BR-NSD	21	2.83	4.88	√
BR.CS/BR.PD	4	4.60(2.78*)	3.73	X
BR-NSD/BR.PD	7	3.50	0.21	X

Drift facies and source sand abbreviations are given in Tables 1 and 5 respectively.
± values are 1 standard deviation; DF = degrees of freedom.
*95% significance level.

BR.PD	Breckland Plateau Drift

The most heavily loaded variables in the Eigen Factors of Corbett (2001a, table 9) have so far been used to define and characterise drift facies. The absolute value of the 1000 mT mean per gram weight was included in the Cluster Analysis (Corbett 2001a) but its Eigen Factor weightings were relatively low. As the lack of differentiation between the LEZ and YRB sands (see above) is relevant to the final interpretation of this study, the absolute 1000 mT (A1000mT) means must now be considered.

Statistically significant differences in the concentration of magnetic minerals (as defined by A1000mT) occur between the LEZ samples and all of the major R clusters (Table 14). With the possible exception of Cluster R2 (NSD) the differences between critical and calculated ‘t’ values (Table 14) are such that, if present, the LEZ magnetic signal has been over-printed; certainly they are not the sole source of the fine sand fraction.

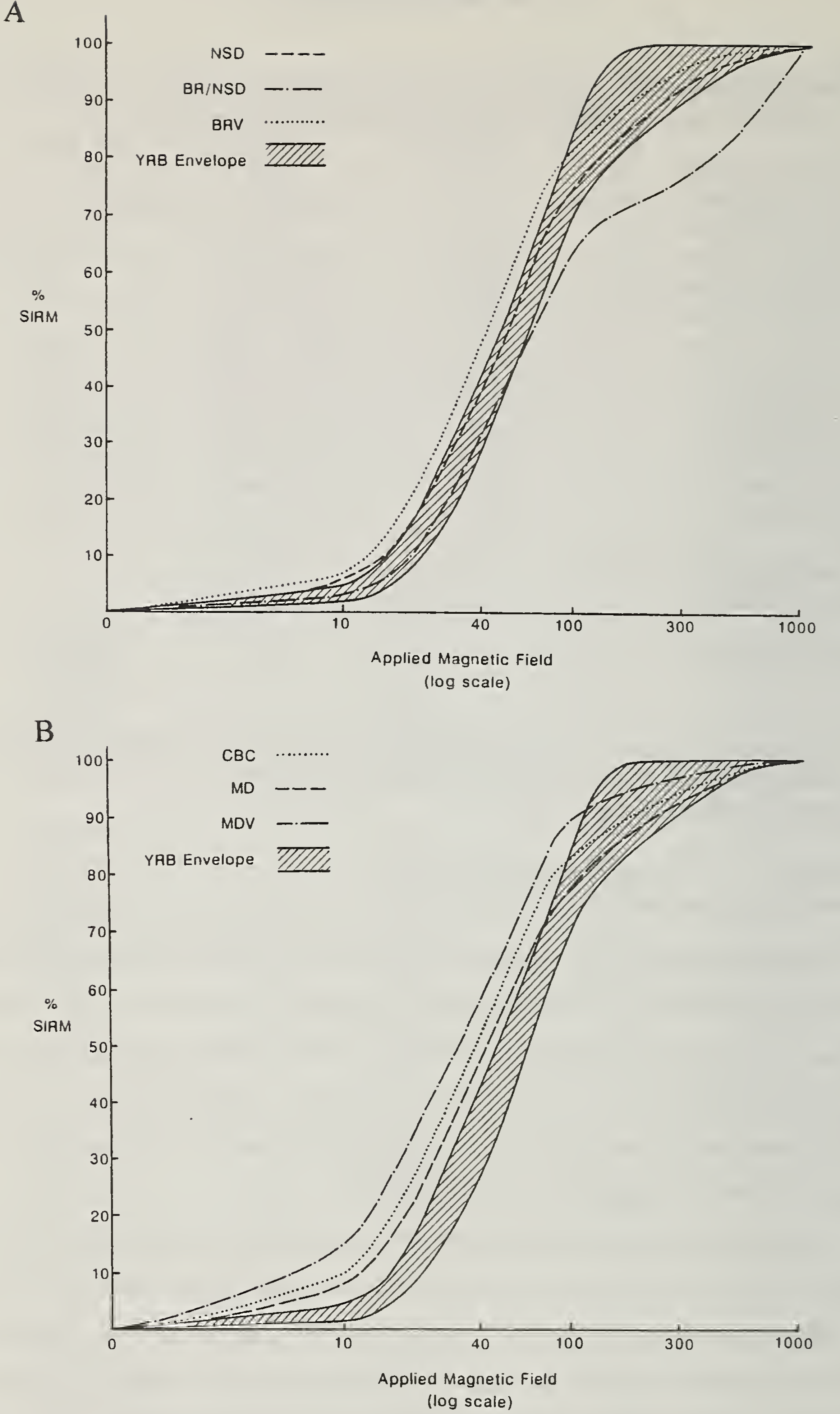


Fig. 5. Magnetic remanence curves for the Yarmouth Road Beds and R Variable derived drift facies of **A)** the North Sea and Breckland drifts and **B)** the Lowestoft Till group.

Table 13. Magnetic remanence means for Ratio/Magnetism derived clusters and source sands.

No.	FACIES	10mT	40mT	50mT	100mT	300mT	1000mT
R1	MD	7.7	47.9	59.3	78.5	91.6	99.6
R2	NSD	5.7	38.0		75.3	93.2	99.2
R3	BRv	6.5	48.4	47.0	82.6	95.3	99.7
R4	UC*	5.3	42.9		84.2	100.0	96.9
R5	BR/NSD	3.3	31.6		64.1	81.7	100.0
R6	CBC	9.5	51.7	54.8	83.4	93.5	99.4
R7	UC*	4.3	43.4		85.3	100.0	95.6
R8	UC*	4.7	37.1		48.7	56.6	100.0
R9	UC*	17.9	64.9	72.7	88.8	97.4	98.7
R10	CBCv	2.1	16.4	30.7	59.4	77.3	100.0
R11	UC*	6.1	55.6		91.3	98.4	100.0
R12	MDv	15.3	58.7		88.9	97.1	99.6
R13	UC*	15.6	79.4		98.6	100.0	95.8
R14	UC*	3.8	36.6		75.5	95.9	100.0
R15	UC*	40.3	77.5		89.9	95.0	100.0

	10mT	40mT	100mT	300mT	1000mT
YRB	4.4	41.3	84.2	100.0	98.9
	1.6	27.7	71.5	89.9	100.0
	0.8	6.5	13.8	17.9	100.0
LEZ	2.6	38.9	84.3	100.0	94.2
	2.1	34.0	80.7	100.0	96.6
CAR	0.2	1.2	12.7	51.2	100.0
	1.0	6.3	16.7	85.2	100.0
	2.0	8.2	15.3	20.4	100.0
	0.5	3.1	5.0	6.2	100.0
SHO.S1	2.3	21.9	37.5	57.2	100.0
SHO.S2	3.3±0.2	55.6±3.1	77.4±4.9	85.7±3.9	100.0
SCAR.F	6.1±2.9	40.2±0.9	78.4±3.3	95.8±0.9	100.0
STA-CLV.F	4.1±0.8	41.2±1.8	84.0±2.0	95.8±2.2	100.0
CLV.F1	2.0±1.4	21.5±3.2	67.9±9.0	96.3±0.4	100.0
CLV.F2	0.2	8.8	69.2	95.9	100.0
CLV.F3	0.2	0.8	7.2	54.0	100.0
BR.CS	3.4±0.5	37.4±1.6	64.1±1.9	78.6±2.5	100.0
BR.PD	2.4±0.4	35.0±3.0	61.7±2.9	78.1±2.9	100.0

*UC – Unclassed. Other drift facies abbreviations are defined in Tables 1 and 5.

± values are 1 standard deviation

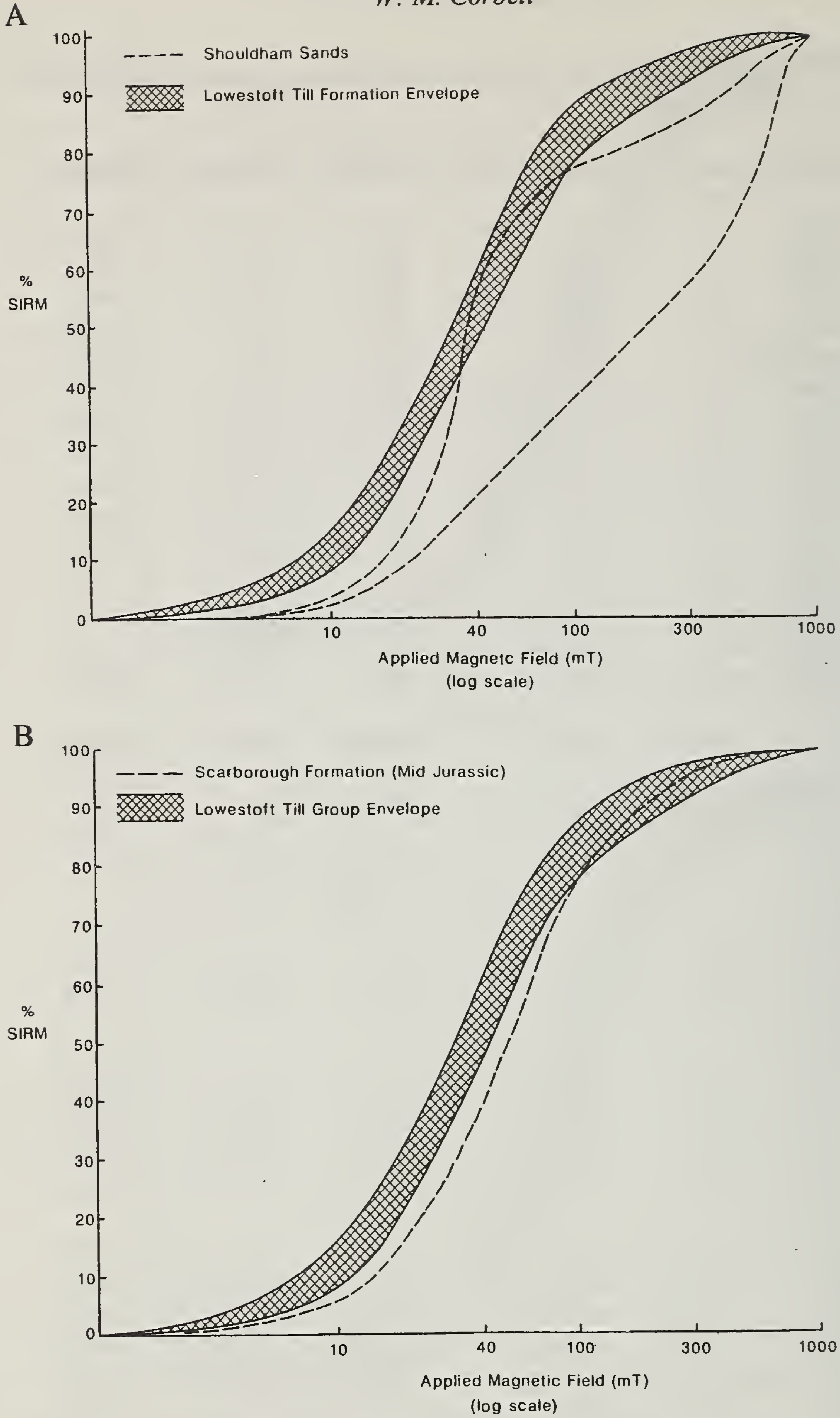
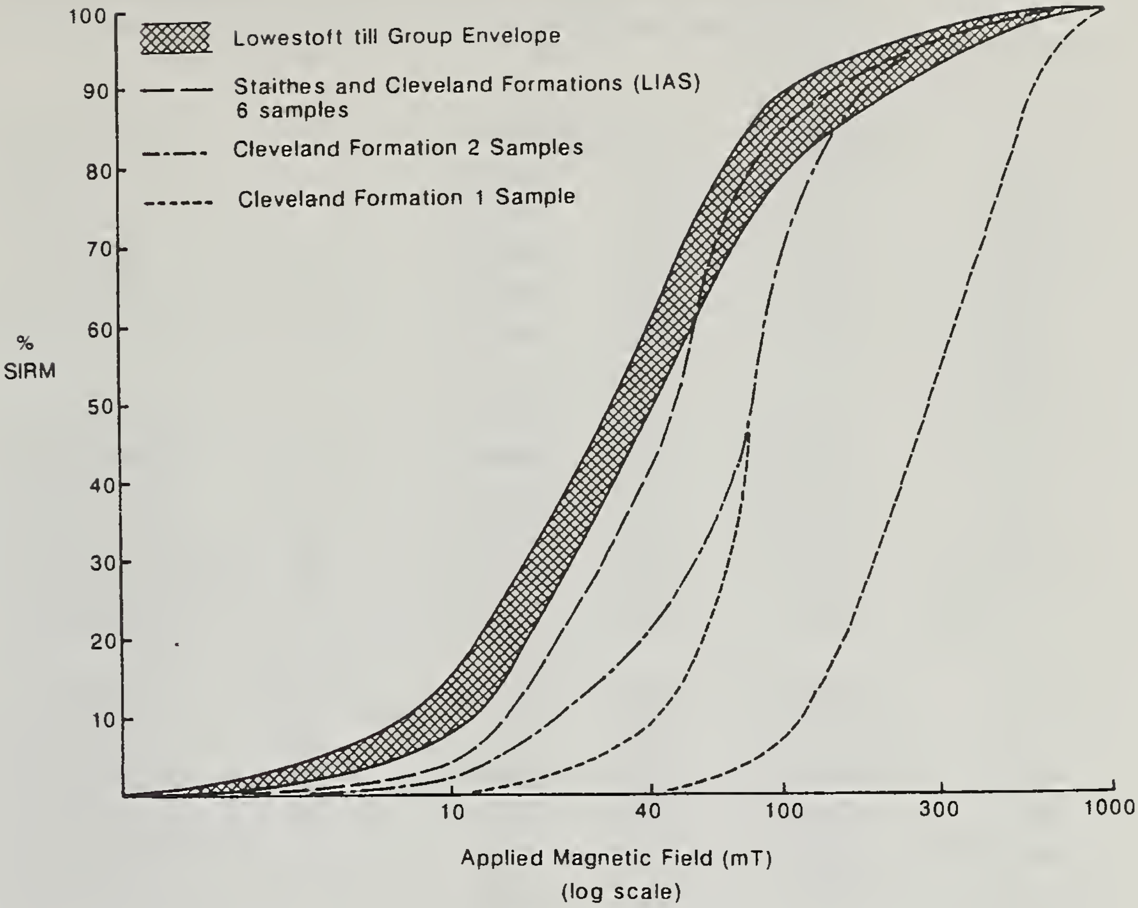


Fig. 6. Magnetic remanence curves for the Lowestoft Till group envelope (R Variables and **A)** the Shouldham Sands; **B)** the Scarborough Formation and **C)** the Staithes an Cleveland Formations. **D)** are the magnetic remanence curves for the Breckland coversan and Breckland and North Sea Drifts.

C


▨ Lowestoft till Group Envelope
Staithes and Cleveland Formations (LIAS) 6 samples
Cleveland Formation 2 Samples
Cleveland Formation 1 Sample
%
SIRM
100
90
80
70
60
50
40
30
20
10
10
40
100
300
1000
Applied Magnetic Field (mT)
(log scale)

D

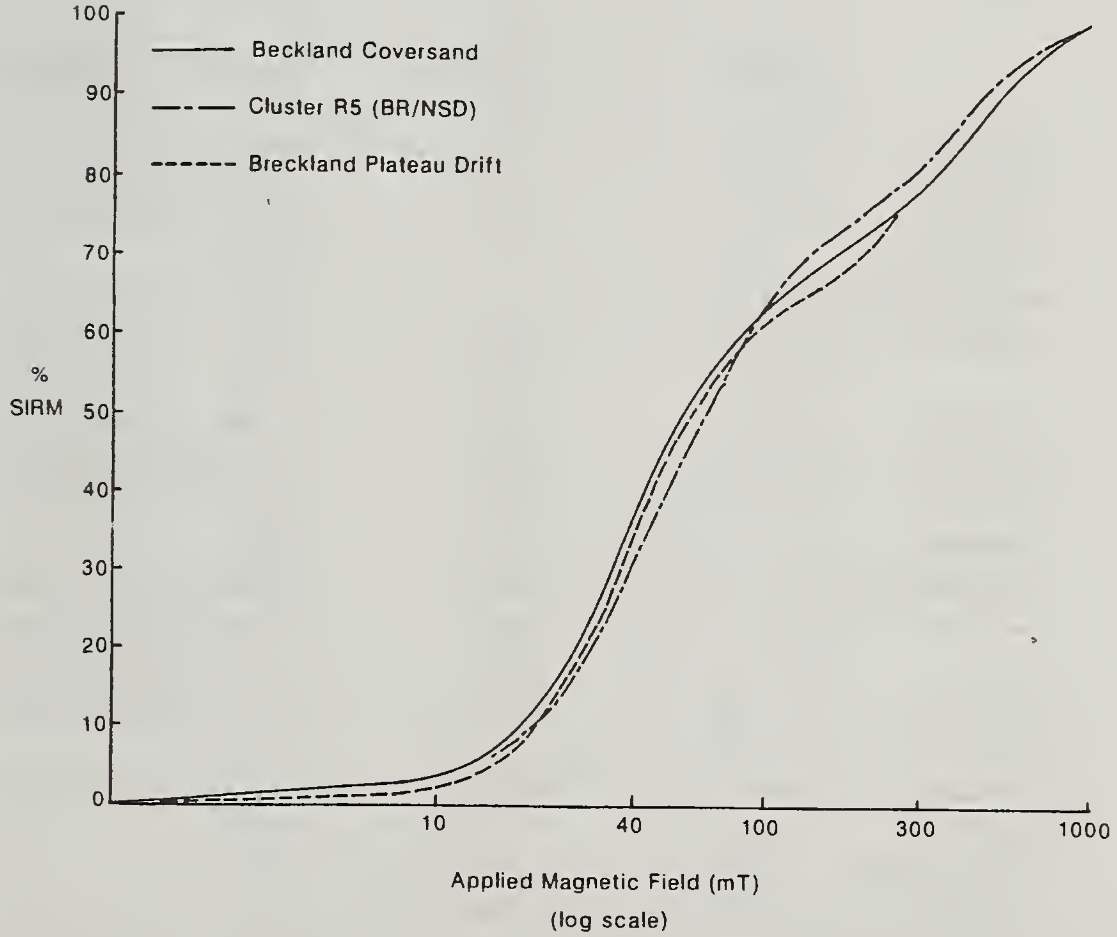

Beckland Coversand
Cluster R5 (BR/NSD)
Breckland Plateau Drift
%
SIRM
100
90
80
70
60
50
40
30
20
10
0
10
40
100
300
1000
Applied Magnetic Field (mT)
(log scale)

Table 14 Significance of differences in A1000 mT means between Ratio/Magnetism derived major drift facies and sand sources.

	CASES	MEANS		
YRB	9	26.6	±23.0	
LEZ	4	5.2	± 1.3	
CAR 1	2	139.2	±42.8	
CAR 2	2	21.7	±10.5	83.0 ±61.8
CAR 3	2	88.2	±52.2	
SHO.S	2	100.3	±11.7	
SCAR.F	6	7.1	±3.4	
STA.F	3	12.9	±0.5	
CLV.F	3	1.8	±0.2	
CLV.F	2	4.4	±2.3	
BR.CS(N)	2	66.9	±5.8	
BR.CS(S)	5	37.4	±7.5	
MDv	21	115.1	±12.8	
MD	257	38.4	±10.9	
CBC	102	72.5	±12.1	
BRv	28	82.8	±15.5	
BR-NSD	16	30.7	±9.3	
NSD	21	22.5	±15.2	
BR.PD	4	40.2	±5.0	

	DF	CRIT 't'	CALC 't'	99% SIG
YRB/MDv	10	3.17	10.8	√
YRB/MD	8	3.36	1.53	X
YRB/CBC	8	3.36	5.91	√
YRB/BRv	10	3.17	6.85	√
YRB/BR-NSD	10	3.17	0.51	X
YRB/NSD	11	3.11	0.49	X
CAR/MDv	5	4.03	1.26	X
CAR/MD	5	4.03	1.76	X
CAR/CBC	5	4.03	0.42	X
CAR/BRv	5	4.03	0.01	X
CAR/BR-NSD	5	4.03	2.06	X
CAR/NSD	5	4.03	2.38	X
LEZ/MDv	8	3.36	38.32	√
LEZ/MD	13	3.01	35.29	√
LEZ/CBC	43	2.69	49.30	√
LEZ/BRv	29	2.76	25.86	√
LEZ/BR-NSD	17	2.90	10.57	√
LEZ/NSD	21	2.83	5.12	√
YRB/LEZ	8	3.36	2.78	X
YRB/CAR	5	4.03	2.14	X
LEZ/CAR	5	4.03	3.08	X

Table 14(Continued)

	DF	CRIT 't'	CALC 't'	99% SIG
SHO.S/MDv	1	63.66	1.70	X
SHO.S/MD	1	63.66	7.46	X
SHO.S/CBC	1	63.66	3.33	X
SHO.S/BRv	1	63.66	1.99	X
SHO.S/BR-NSD	1	63.66	8.10	X
SHO.S/NSD	1	63.66	8.73	X
SCAR.F/MDv	25	2.79	34.63	√
SCAR.F/MD	8	3.36	20.25	√
SCAR.F/CBC	15	2.95	35.67	√
SCAR.F/BRv	32	2.75	23.35	√
SCAR.F/BR-NSD	20	2.84	8.72	√
SCAR.F/NSD	25	2.79	4.28	√
STA.F/MDv	20	2.84	36.40	√
STA.F/MD	78	2.66	34.54	√
STA.F/CBC	100	2.62	48.37	√
STA.F/BRv	27	2.77	23.75	√
STA.F/BR-NSD	15	2.95	7.60	√
STA.F/NSD	20	2.84	2.88	√
CLV.F/MDv	20	2.84	40.56	√
CLV.F/MD	268	2.62	53.77	√
CLV.F/CBC	103	2.62	58.99	√
CLV.F/BRv	27	2.77	27.65	√
CLV.F/BR-NSD	15	2.95	12.43	√
CLV.F/NSD	20	2.84	6.24	√
CLV.F/MDv	11	3.11	34.25	√
CLV.F/MD	1	63.66	19.29	X
CLV.F/CBC	2	9.92	33.72	√
CLV.F/BRv	13	3.01	23.40	√
CLV.F/BR-NSD	7	3.50	9.63	√
CLV.F/NSD	14	2.98	4.90	√
BR.CS(N)/BR-NSD	2	9.92	7.68	X
BR.CS(N)/BR.PD	2	9.92	5.56	X
BR.CS(S)/BR-NSD	8	3.36	1.64	X
BR.CS(S)/BR.PD	7	3.50	0.67	X
BR-NSD/BR.PD	9	3.25	2.78	X

Drift facies and reference site abbreviations are given in Tables 1 and 5 respectively. ± values are 1 standard deviation; DF = degrees of freedom.

BR.CS(N),(S)	Breckland Coversand (North), (South)
BR.PD	Breckland Plateau Drift

For the YRB there are significant differences in the concentration of magnetic minerals with Clusters R12 (MDv), R6 (CBC) and R3 (BRv). However, compared with the scale of difference between the calculated and critical 't' values for the LEZ samples, the difference is much less (Table 14). As concluded from the magnetic remanence curves, the YRB could have supplied fine sands to the drifts, mixed with other non-local sources.

The Shouldham Sands (SHO.S) show no significant differences in the concentration of magnetic minerals to any of the drift facies. At least part of the reason for this is the very high critical 't' value given by only one degree of freedom. In complete contrast, however, almost all of the Jurassic sandstones differ significantly from all of the drifts. The only exception is the apparent link between the Cleveland Formation (CLV.F) subset and Cluster R1 (MD), which is statistically doubtful because of the very high critical 't' value. Data for the Breckland coversands (BR.CS) and drift facies (Table 14) shows there is no significant difference between the coversand and the Breckland plateau drift (BR.P.D.), or between the coversand and Cluster R5 (BR/NSD); nor is there a significant difference between BR.P.D. and Cluster R5 (BR/NSD).

Ranking the major R Variable-derived drift facies according to their calculated 't' values for MDF compared with the YRB (Table 15) reflects degrees of difference in the 'soft' remanence or magnetite content. A similar ranking based on the A1000 mT data

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Table 15. Comparison of calculated 't' values for major Ratio/Magnetism derived drift facies and YRB for MDF and A1000 mT.

	MDF 't'	**SIG DIFF**		**CONC (A1000mT) MAG MIN** 't'	**SIG DIFF**
MDv	11.3	√	MDv	10.8	√
CBC	9.07	√	BRv	6.85	√
MD	7.83	√	CBC	5.91	√
BRv	7.21	√	MD	1.53	X
BR/NSD	4.04	√	BR/NSD	0.51	X
NSD	1.4	X	NSD	0.49	X

Drift facies abbreviations are defined in Table 1.

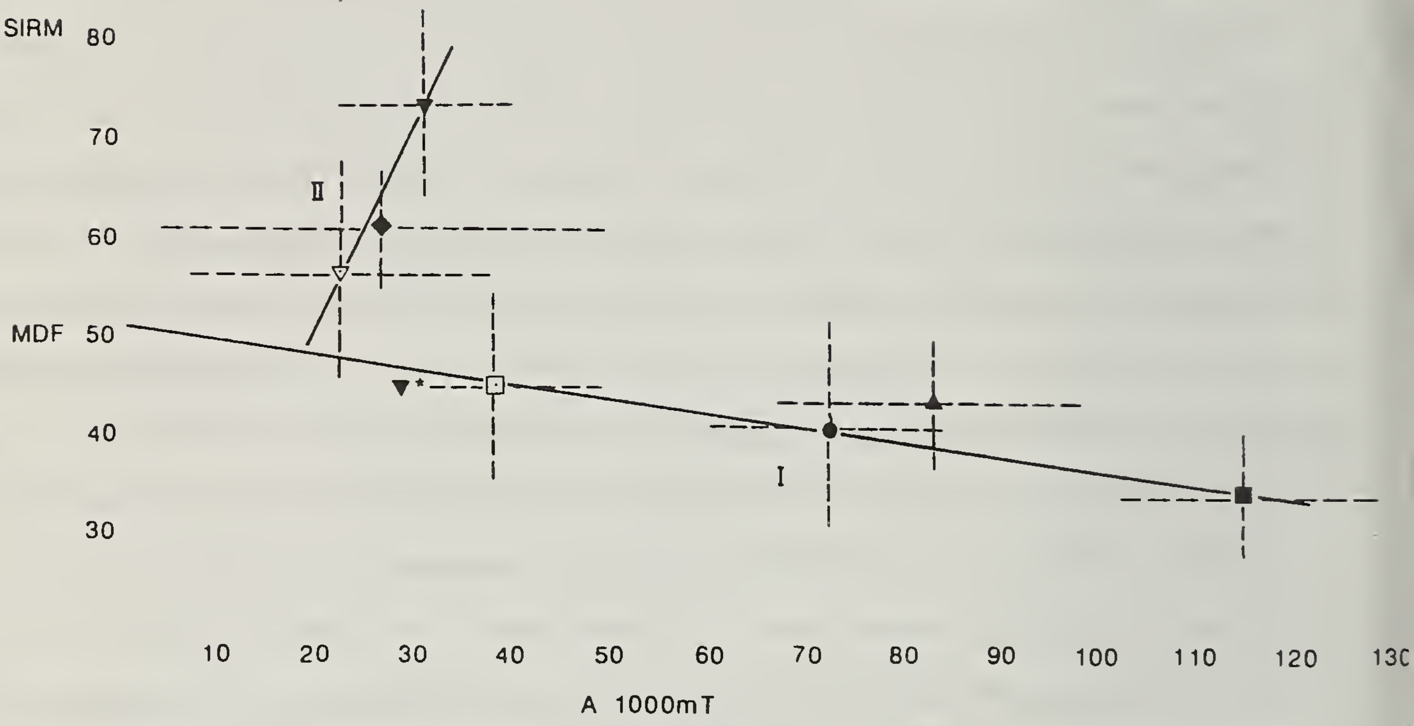
produces the same order of drift facies (excepting Cluster R3 (BRv)). This common ranking suggests; either 1) differing degrees of admixture of a non-local fine sand with material derived from the YRB; or 2) quite separate fine sand sources, as recognized in the Cluster Analysis, but with sufficient variation to give an overlap in their magnetic character.

Cross plotting the mean MDF and A1000 mT values for the major R clusters and for the YRB data shows that for Clusters R12 (MDv), R6 (CBC) and R1 (MD) (Fig. 7A, Plot I), there is a linear relationship. This linear function has a gentle negative gradient of MDF values over a wide range of increasing SIRM, probably reflecting increasing concentrations of easily magnetised 'soft' IRM, magnetite, from MD to CBC to MDv (Fig. 7A).

Cluster R2 (NSD), the YRB and Cluster R5 (BR/NSD) (Fig. 7A, Plot II), also have a linear relationship, but with a steep positive gradient. The MDF values are higher, indicating the presence of hard remanence magnetic materials, such as haematite and goethite or possibly magnetite of a different grain size from that in Clusters R12 (MDv), R6 (CBC) and R1 (MD) (Fig. 7A Plot I). The spread of MDF values in Plot II (Fig. 7A) is comparable to that in the 'Lowestoft Till' group (Plot I, Fig. 7A) although systematically higher. However, in Plot II the concentration of magnetic minerals (A1000mT) is much lower and the spread of values much narrower. The trend of MDF/A1000mT in Plot II is interpreted as being due to variations in the type of magnetic minerals present within a narrow and low range of concentrations. Such variation is to be expected from sand sources in the North Sea depositional basin which is fed by several large rivers. The position of the Cluster R3 (BRv) on Figure 7A is also interesting as it lies just above (but within error margins) of the MD-CBC-MDv linear trend.

The MDF/A1000mT regression lines for the 'Lowestoft Till' group (Plot I, Fig. 7A) and for the Breckland-North Sea Drift group (Plot II, Fig. 7A) are compared to all the sampled sources of fine sand in Figure 7B (data in Tables 12 and 14). Clearly the Shouldham Sands data (Fig. 7B) plots in close association with that part of the 'Lowestoft Till' group regression line between Cluster R6 (CBC) and Cluster R12 (MDv). The Scarborough and Staithes Formation data lie on, or near, a **projection** of the 'Lowestoft Till' group regression line (Fig. 7B) suggesting that these rocks may have contributed some sand, the mixture being apparently balanced by the magnetic character of the Shouldham Sands.

	1000mT (A)	MDF	Symbols
MDV	115.1	34.6	■
MD	38.4	46.0	□
CBC	72.5	41.7	●
BRV	82.8	44.3	▲
BR/NSD	30.7	74.6	▼
NSD	22.5	57.5	▽
West Runton Sample	29.2	46.1	▼ *
YRB	26.6	62.1	◆



-----Standard Deviations

PLOT I
Regression Equation 1 $MDF = 52.0 - 0.149\ A\ 1000mT$
($R^2 = 99.4$, Confidence level 95%)

PLOT II
Regression Equation 2 $MDF = 9.3 + 2.09\ A\ 1000mT$
($R^2 = 93.4$, Confidence Level 83%)

Fig. 7A. Plot and regressions of MDF and A1000mT means for major R derived drift facies and the Yarmouth Road Beds.

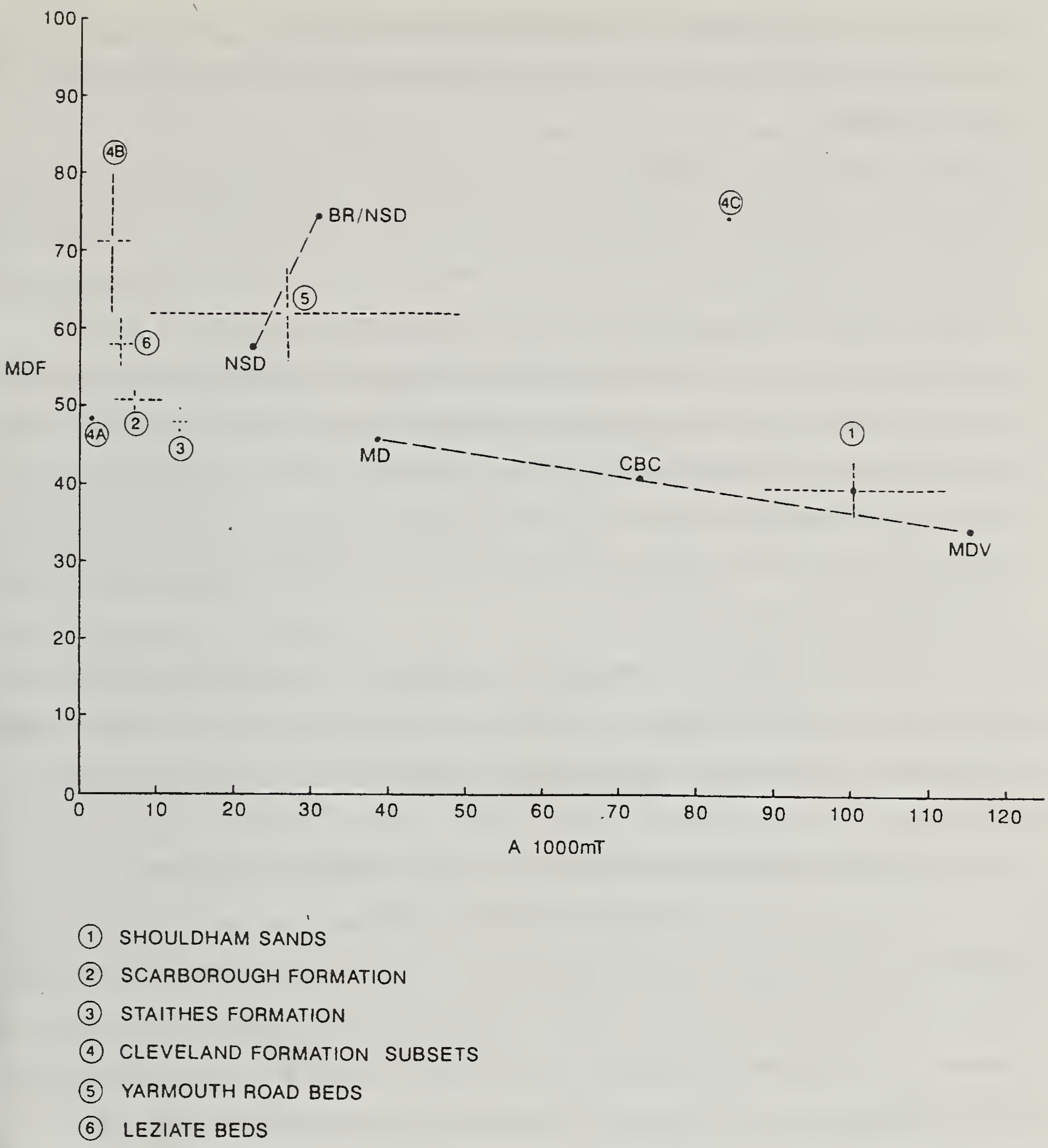


Fig. 7B. Plot of MDF and A1000mT means and standard deviations for sources of the sand fractions for the Lowestoft Till and Breckland-North Sea Drift groups.

(One sample from the Shouldham Sands had an MDF value of 200.9 mT and one from Cleveland Formation an MDF value of 273.2 mT and an A1000 mT value of 192.8 mT. These values are far beyond the range of values of the other source sand samples and of those of the drift facies. These samples were excluded from the plot although they are of interest in terms of source variability. Their remanence curves are plotted in Figures 2B and 1D).

The principal points emerging from the interpretations above are:

1. The CAR and LEZ sands made little or no contribution to the fine sand fraction in the major R clusters.
2. The magnetic character of the fine sand fraction indicates two quite separate sources and these are represented by the separate groupings of the major R clusters. In the NSD/BR grouping the magnetic character of the fine sand fraction is similar to that of the YRB although some variants may contain a mixture of non-local sands also.
3. The magnetic character of the fine sand fraction in the 'Lowestoft Till' group could have been derived in part from the Jurassic sandstones in east Yorkshire and perhaps, more especially, from the Shouldham Sands in west Norfolk. However the remanence curves show there is an additional source of multi-domain magnetite that is unaccounted for. Possible sources for this magnetite are the basic and intermediate igneous rocks in north east England and eastern Scotland.
4. Cluster R3 (BRv) drift facies is an exception. Although its magnetic character is close to that of the 'Lowestoft Till' group its RFTOC and other ratio properties (Table 10) place it in an intermediate position between these two drift facies.

Genetic differences between Measured and Ratio/Magnetism Variable-derived drift facies

Drift facies derived from M and R Variables, show no direct equivalence (Corbett 2001a). There is, however, general correspondence at the level of groupings of drift facies, the 'Lowestoft Till' group and the Breckland-North Sea Drift group being easily recognisable in both classifications.

Equivalence between groups of M clusters and R clusters based on reference samples and matching, allows comparison of character, and differences can be put into a genetic context. M Variable-derived drift facies, in themselves well differentiated, are distinctive only to a limited degree in terms of the magnetic character of their fine sand fractions. Variables that describe gross lithology (e.g. total carbonate or Mesozoic clay content), are on the whole determined locally, since nearby substrates determine the gross lithological composition of a till. In contrast, magnetic composition should be affected by derivation of magnetic minerals originating from igneous and metamorphic rocks which by definition will be distal source areas to East Anglia. Clearly a classification based largely on characteristics derived from the local geology will not discriminate distal influences. By contrast, a classification based on R Variables and magnetic character (which is less biased and more truly reflects source inputs including those of distal origin) produces units that are weakly differentiated in terms of gross lithology derived mainly from local sources. The problem is to decide which of the two classifications is the more valid or useful in a spatial and stratigraphic sense.

While R cluster units appear to show some generally constant spatial and stratigraphic patterns, the M clusters do not (Corbett 2001b). Lack of spatial differentiation could be caused by local ice flow paths which in time and space remain similar in relation to the underlying geology. Moreover, younger glacial tills may incorporate sediment deposited from older tills. If this is so, it follows that earlier published classifications based on the more obvious contrasts in gross lithology, record mainly local source variability and may not reflect stratigraphic chronology.

Where the local source materials include older tills or glacial sediments the studied drifts may have a mixed character. This interpretation has already been used to explain Cluster R3 (BRv) in Breckland (Corbett (1996) and it may also account for the occurrence of Clusters R1 (MD), R6 (CBC) and R10 (CBCv) at the reference sites in north-east Norfolk. The origin of the most widespread chalk sand drift in Breckland (Cluster R5(BR/NSD) is still uncertain. If it resulted from periglacial mixing of coversand and chalk, the link to the North Sea Drift, indicated by Cluster R5 (BR/NSD), could be accounted for by a common sand source, the Yarmouth Road Beds (YRB).

DRIFT FACIES SPATIAL DISTRIBUTION AND STRATIGRAPHY

The surface distribution of drift facies in the study area comprises a fairly continuous sheet of Chalky Boulderclay spanning the central plateau area (Fig. 8). Undifferentiated North Sea Drift group occurs N and E of Norwich, with some outliers to the W - mainly on lower slopes of the plateau (Fig. 8).

Cluster analysis of the R Variables (Corbett 2001a) equated a reference sample from the Second Cromer Till of the North Sea Drift at Overstrand (Reid 1882; Banham 1968), with the most widespread Breckland Drift i.e. Cluster R5 (BR/NSD; Corbett 2001a). This drift facies also occurs within the Chalky Boulder Clay Plateau on the lower slope at Flordon

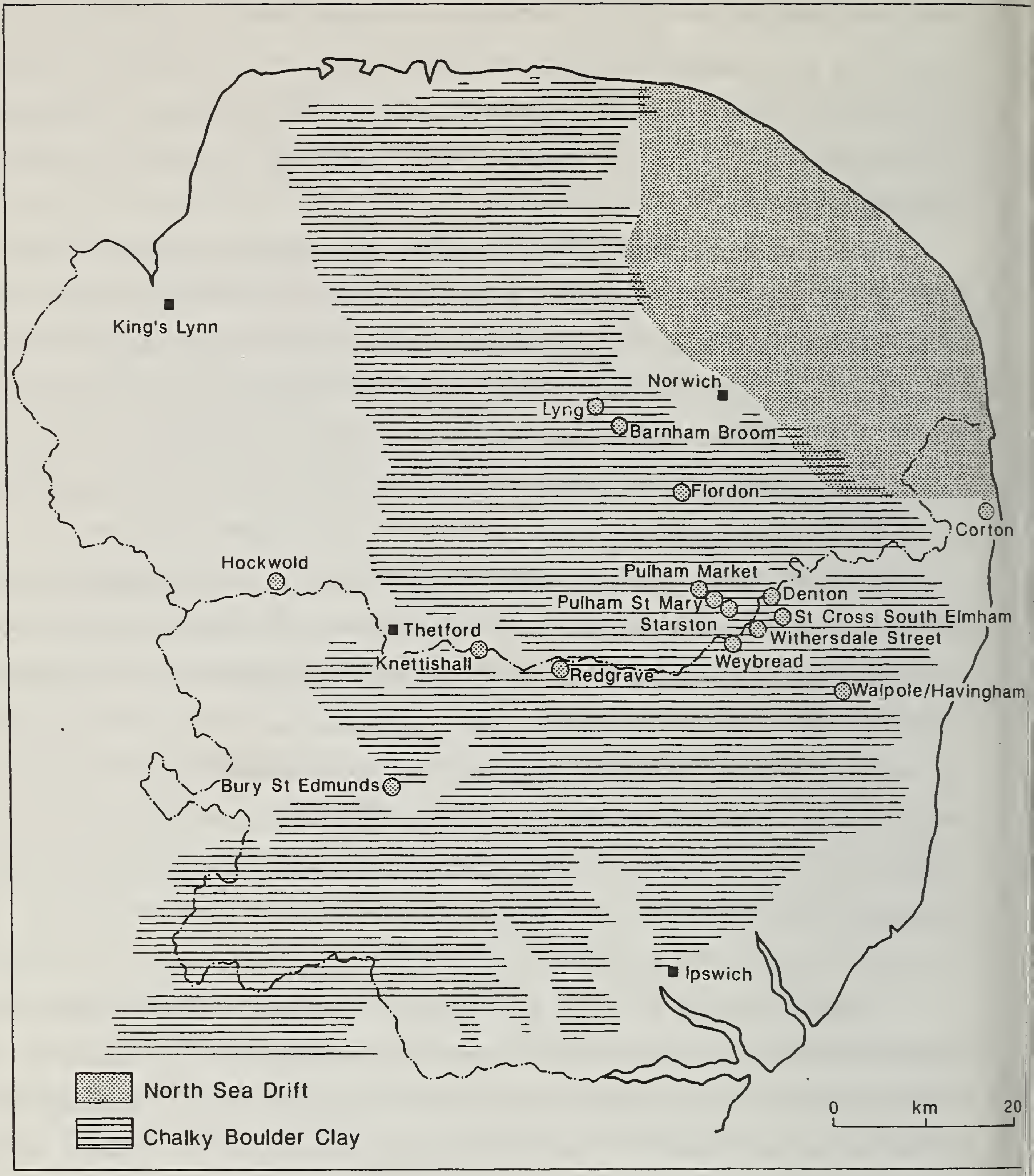


Fig. 8. Sketch map to show surface distribution of the Chalky Boulderclay a undifferentiated North Sea Drift in Norfolk and Suffolk. Circles indicate locations whe North Sea Drift has been identified outside the main area by various authors. Many of the are in the Waveney Valley.

(Fig. 1) and, again in north Norfolk at Swanton Novers (Fig. 1; Corbett 2001b). Similarly, the First Cromer Till of the North Sea Drift (Reid 1882; Banham 1968) occurs in the south at Knettishall (Fig. 1) and, in the north at Swanton Novers and at Briston (Fig. 1; Corbett 2001b). These isolated occurrences of North Sea Drift in central Norfolk and in Suffolk suggest the presence of a much more widespread surface distribution of North Sea Drift ice. Many previous workers have reached similar conclusions when studying specific locations (Fig. 8): these include Bennett (1884) at a site near Hockwold; Whitaker and Dalton (1887), Baden-Powell (1950), Coxon (1981), Clarke and Auton (1982) and Mathers *et al.* (1993) at several locations in or near the Waveney Valley; Perrin *et al.* (1979) at Flordon and Hockwold; Mathers *et al.* (1987) for an area north west of Diss; Lewis and Rose (1991) at Knettishall, and Boswell (1923) who claimed that North Sea Drift ice covered much of Norfolk and north Suffolk.

The general stratigraphy at the Corton type site near Lowestoft (Fig. 1; Banham 1971, Mitchell *et al.* 1973), displays 'Lowestoft Till' overlying a member of the North Sea Drift Formation and this arrangement occurs at all sites inland where till members of both groups are present (Corbett 1996). North of the Corton site the North Sea Drift group stratigraphy consists of three till members, the First, Second and Third Cromer Tills (Reid 1882; Banham 1968). A fourth member composed of highly deformed beds of these three Cromer Tills, is a kinetostratigraphic unit referred to as the Contorted Drift. An inland member of the North Sea Drift, known as the Norwich Brickearth, has been associated with the First and Third Cromer Tills (Perrin *et al.* 1979) and also the First Cromer Till (Hopson and Bridge 1987). This has direct relevance to this study's interpretation of drift origins in Breckland. Cluster R3 (BRv), could have been formed by mixing of debris from the Chalky Boulderclay with Cluster R2 (NSD equivalent of the First Comer Till; Corbett 2001a), rather than with Cluster R5(BR/NSD) (containing the Second Cromer Till; see Corbett (1996) for a detailed discussion).

The stratigraphic significance of this interpretation is that, in Breckland, the depositional sequence seen on the north-east Norfolk coast has to be reversed. This possibility has to be weighed against the more likely one that the depositional sequence is the same as that on the north-east Norfolk coast and that the mixing occurred with the Third Cromer Till which was not sampled by Corbett (2001a). However, Perrin *et al.* (1979)

considered the First and Third Cromer Tills to have “virtually the same particle size distribution”. This would help explain the stratigraphy at Swanton Novers (Corbett 2001b) where Cluster R2 (NSD equivalent of the First Comer Till) overlies Cluster R5 (BR/NSD) (containing the Second Cromer Till).

Geological Survey mapping of the Lowestoft Till Formation has recognised only one till, the ‘Chalky Boulder Clay’. Other tills are termed “minor local variants” (Bristow and Cox 1973). This ignores references going back almost 150 years to a more chalky member with certainly a local - and possibly a regional - distribution and fairly distinct stratigraphic position. Trimmer (1846) and Harmer (1909) gave its distribution as being northern Norfolk, the latter giving it a southern boundary along a line running west inland from Lowestoft. Other limits include the area to the north of Fakenham and Docking (Perrin *et al.* 1979), to the west of Norwich, Diss and Bury St Edmunds, (Straw 1983), and the Gipping Valley (Ehlers and Gibbard 1991) - areas that can be located on Figure 1. The terms Marly Drift (Boswell 1914; 1916) and Gipping Till (Baden-Powell 1948) both refer to more chalky till members than the Chalky Boulderclay. The Marly Drift also has a characteristic lack of Jurassic debris (Trimmer 1846; Harmer 1909; Straw in Cox and Nickless 1974). Ehlers *et al.* (1991) summarise the Marly Drift composition as being extremely high in chalk and flint with an “almost complete absence of any other lithological components”. Banham *et al.* (1975) recognize a North Sea Drift member and a Lowestoft Till member of the Marly Drift and also an intergrade, as well as a till consisting almost entirely of reconstituted chalk. Indeed, to the north of Fakenham and Docking (Fig. 1) they recognise a western area containing the Lowestoft Till member and the intergrade unit and an eastern area containing the North Sea Drift member and the intergrade. They identified two sections (one in north-east Norfolk at West Beckham (TG138398) on the crest of the Cromer ridge) where the North Sea Drift member passes up into the Lowestoft Till member, but found no cases of the reverse situation.

Ehlers *et al.* (1991) also recognized two types of Marly Drift, presumably within the Lowestoft Till member of Banham *et al.* (1975), which in south Norfolk are superimposed. The lower one contains abundant Jurassic erratics and is a chalk-rich equivalent of the Lowestoft Till. Although Ehlers *et al.* (1991) also claim that superimposition of Marly Drift on Lowestoft or Cromer Till is rare, a number of earlier workers noted this stratigraphic arrangement at various localities: these include Blake (1888) around East Dereham; Baden-

Powell (1948) in the Gipping Valley; Banham (1971) at Corton (near Lowestoft), and Evans (1975), Gallois (1978), Straw (1979) and Ventris (1986) at Bawsey – all shown on Fig. 1. Blake (1888) also noted the two till members in no clear stratigraphic order in the East Dereham area (Fig. 1).

Measured Variable Cluster Analysis Corbett (2001a) has differentiated drift facies equivalents of the Chalky Boulder Clay and two forms of Marly Drift, Clusters M8 (MD) and M15 (MDv). The latter, based on particle size summation curves, is associated with Banham's North Sea Drift type of Marly Drift (see discussion in Corbett 2001a). Cluster Analysis using R-derived Variables also identified three drift facies, but cross comparison of the two forms of Cluster Analysis (Corbett 2001a) showed no equivalence between Cluster M15 (MDv) and Cluster R12 (MDv). By contrast, fairly good equivalence was demonstrated between Cluster M8 (MD) and R1 (MD) and also some equivalence between Cluster M7 (CBC) and R6 (CBC) (Corbett 2001a). Reference samples from Great Blakenham (Fig. 1) showed that on the plateau and below the surface drift on the slopes, the two classifications match, but that R clusters best differentiate the surface drift on slopes. As shown above the variables that best differentiate R clusters are MDF and mean A1000 mT (i.e. absolute concentration of magnetic minerals). When these variables are plotted (e.g. Fig. 7A) Cluster R12 (MDv) is more closely associated with Cluster R6 (CBC) rather than with Cluster R1 (MD).

The stratigraphic arrangement of these facies in west and central Norfolk and in central Suffolk was detailed by (Corbett 2001b) who demonstrated that although the drift facies are not present in discrete stratigraphic layers, their general order of superimposition is Cluster R1 (MD) over R12 (MDv), over R6 (CBC). Again Cluster R12 (MDv) is most closely associated with Cluster R6 (CBC) rather than with Cluster R1 (MD). This supports the findings of Ehlers *et al.* (1991) who recognised a lower division of Marly Drift with abundant Jurassic erratics. In effect the 'Lowestoft Till' group is divisible into an upper unit (Cluster R1 (MD)) with no Jurassic component and a lower unit (Cluster R6 (CBC)) with less carbonate and more non-carbonate fine sands of presumed Jurassic origin. The lower unit may have some Cluster R12 (MDv) incorporated in its surface. The combined cluster association and stratigraphic position of Cluster R12 (MDv) indicates a late depositional stage of the Chalky Boulder Clay ice rather than an early deposition stage of the Marly Drift ice.

Apart from the absence or near absence of Cluster R12 (MDv) towards the east (Flordon; Fig. 1) and south (Tannington; Fig. 1) of the study area, the stratigraphic order derived from Cluster Analysis of the R variables across the plateau in Norfolk and Suffolk, is consistent (Corbett 2001b). However, lateral trends in data means for the upper 4m of tills in this same area (Perrin *et al.* 1979) were not seen in the Cluster Analysis. Although gross lithology variables explain by far the largest percentage of variance, (Eigen Factors 1 and 2 together explain almost 54% – see Corbett 2001a, table 9), their most heavily weighted variables are the fine and course fractions of both carbonate and non-carbonate material (Corbett 2001a, table 9). Total carbonate, as used by Perrin *et al.* (1979), is the most heavily weighted variable in Eigen Factor 5 of Corbett (2001a, table 9), but explains only 6.2% of the variance. Obviously the Cluster Analysis of R variables in this study has missed the lateral trends in total carbonate and in non-carbonate sand found by Perrin *et al.* (1979), these trends in effect being included within Cluster R1 (MD).

The relative uniformity in gross lithology, suggests that the stratigraphic sequence represents either basal melt-out or lodgement tills. It is, of course, possible that the lower parts of the deep boreholes have penetrated deformation tills, similar to those recognised at Great Blakenham (Hart *et al.* 1990). However, the Great Blakenham reference samples were taken from the homogeneous tills in the upper part of the exposure (Corbett 2001a). By contrast, the taxonomically similar unit to this reference sample, Cluster R6 (CBC), is found towards the bottom of the deep boreholes on the Boulderclay plateau further north in Norfolk and Suffolk. Here, these Cluster R6 (CBC) sediments overlie at greater depth either chalk, glacial outwash or preglacial sand and gravel. There is no evidence that any of the deepest till samples have incorporated the older underlying sediments. Neither were fundamental features of deformation tills seen (e.g. penetrative cleavage of the subglacial rock above a plain of decollement (Whiteman 1987)). Together these observations imply that the deep boreholes did not reach deformation till. This conclusion seems sensible as the general thickness of the Lowestoft Till on interfluves is about 30 m, while the maximum sampling depth was 22 metres, leaving in excess of 8 m unsampled. Since the depth of deformation is typically 1 to 10 m (Hart *et al.* 1990) it is unlikely that deformation tills were sampled.

ANGLIAN ICE MOVEMENT AND SOURCE AREAS

Lowestoft Till Formation

Earlier work on Anglian ice movement (Table 16), despite being based on different methods, suggests strongly that the direction of ice flow distal to East Anglia was from the NW and that distal source areas included the east coast of the British Isles from Scotland southward. A minor qualification is a potential contribution from the Pennines (Harmer 1909; Rose 1992) perhaps a separate early stage of the Anglia Glaciation.

The results of this study (outlined above) show that the R Variable magnetic character of the fine sand fraction in the 'Lowestoft Till' group could have come in part from the Shouldham Sands and from the Jurassic sandstones in east Yorkshire. However, there is also a component of 'soft' multi-domain magnetite derived from an unrecognised source. The magnetic character of the 'Lowestoft Till' group differs from the 'North Sea Drift' group in having a higher concentration of magnetite minerals, a slightly narrower range in the MDF (and therefore mineral composition) and a variability between till members determined by the amount of magnetite and perhaps also by its grain size. Obvious sources of magnetite are the intermediate and basic igneous rocks of north-east England and eastern Scotland, although these rock types are also present in southern Norway. However, if marked differences in magnetic character (linear functions in Fig. 7A) are interpreted as two separate distal sources, and if one of these is accepted as the floor of the North Sea (see above), the other, as most previous work claims, is probably eastern Scotland and north-east England. It is of interest to note in the 'Lowestoft Till' group the Marly Drift equivalent, Cluster R1 (MD) is the nearest in magnetic character to the North Sea Drift Group.

The above interpretations contradict those of Perrin *et al.* (1973; 1979) who suggested that the heavy mineral suites of the North Sea Drift and Lowestoft Till Groups are qualitatively similar. The suggestion that the Lowestoft Till magnetite detected in this study derives from northern Britain disagrees with the idea that heavy minerals in the fine sand fraction of the Lowestoft Till were sourced from the floor of the North Sea (Perrin *et al.* (1979).

The **local** directions of ice movement for the 'Lowestoft Till' are here defined as those ice movements that occurred south of the line of the present north Norfolk coast.

Table 16. Previous work on the directions of Anglian ice movement.

		NSD	NBE	CT1	CT2	CT3	CD	CBC	MD1	GT	MD2
Harmer	1902						NW	N			
Harmer	1904	NE						NW			
Harmer	1909	NW									NW
Baden-Powell	1948							NW		N(East Coast)	
Funnell	1955							W		NW	
West & Donner	1956	NW						NW-SW		N	
Ransom	1967				NW	W					
Straw	1967										N
West & Banham	1968					NW					
Kazi & Knill	1969			WNW							
Straw	1973										N
Perrin et al	1973	North Sea						North Sea			
Allen	1973							NW			N-NNW
Cox & Nickless	1974	NE									
Evans	1975							W to NW			
Banham et al	1975			NE	NW		NW				N
West	1977			NE	NW	W					
Allen	1988							NW			
Gallois	1978							NW			
Perrin et al	1979	North Sea						North Sea			

Straw	1979					WNW			N
Straw	1979a								NE England E Scotland
Straw	1979b	N-NE				NW			
Straw	1983								N
Bowen et al	1986	Scand				Scot			
Hart J.K.	1987		NW	NE					
Ehlers & Gibbard	1991	NE				Vale of York			
Ehlers et al	1991	NNE					SW	NW-N	NW
Straw	1991					NW			
Lunkka	1994		NE	NW	NW/N				

NSD - North Sea Drift;
NBE - Norwich Brickearth;
CT1,2,3, - First, Second and Third Cromer Till;
CD - Contorted Drift; CBC - Chalky Boulderclay/Lowestoft Till;
MD1 - Younger Marly Drift;
GT - Gipping Till;
MD2 - Marly Drift (older).

There is general agreement that Lowestoft Till ice approached East Anglia from between the N and W. While some workers (Harmer 1902; West and Donner 1956; Straw 1991) imply movement of Lowestoft Till ice across Fenland and the Wash gap, obliquely onto the Cretaceous escarpments (Fig 9a), others, in particular Perrin *et al.* (1979), think the ice came from a northerly direction directly through the Wash gap into Fenland (Fig. 9b). To some extent these differences were reconciled by Rose (1992) who invoked an earlier stage of Pennine ice from the NW, and a later stage of Scottish ice which entered Fenland around the Wash gap.

Ice erosion of the west Norfolk Cretaceous escarpments Gallois (1978) left a local dark grey till below the escarpment with a component derived from the Lower Cretaceous Sands (Evans 1974; Gallois 1978). However, most of Lowestoft Till contains little Lower Cretaceous material (Straw 1979a) a finding corroborated in this study in that the fine sand fraction of the Lowestoft Till differs magnetically from both the Leziate Sands and the Carstone. This suggests it is unlikely that Lowestoft Till ice entered upland Norfolk obliquely across the Cretaceous escarpment. For the alternative ice route of Perrin *et al.* (1979) to be valid, the Norfolk and Suffolk ice must have either; 1) passed through a Wash gap already eroded by ice that deposited its tills elsewhere; or 2) climbed the Cretaceous escarpments out of Fenland, without eroding them enough to incorporate large amounts of Cretaceous sands in the tills. These speculations could be tested with further sampling particularly to the south and west of Fenland, an area not included in this study.

Lowestoft Till ice movement from Fenland across Norfolk and Suffolk appears to have been easterly (Fig. 9), part of a radial spread from Fenland (Perrin *et al.* 1979). This spreading effect was probably caused by the unlithified impermeable Jurassic clay substrate in Fenland (Boulton 1975; 1979). Moreover, eastward ice flow from Fenland was probably encouraged by the damming effect of that part of the chalk escarpment to the south of Fenland which was not over-ridden. This eastward ice flow was divided into two stages by West and Donner (1956), on the basis of stone orientation fabrics. Initially flow was to the SE and E and later to the ENE (Fig. 9a). An ENE ice-path was also noted for the northern part of the Chalky Jurassic Drift (Baden-Powell 1948) and likewise by Ehlers *et al.* (1987) for their lower Jurassic type Marly Drift.

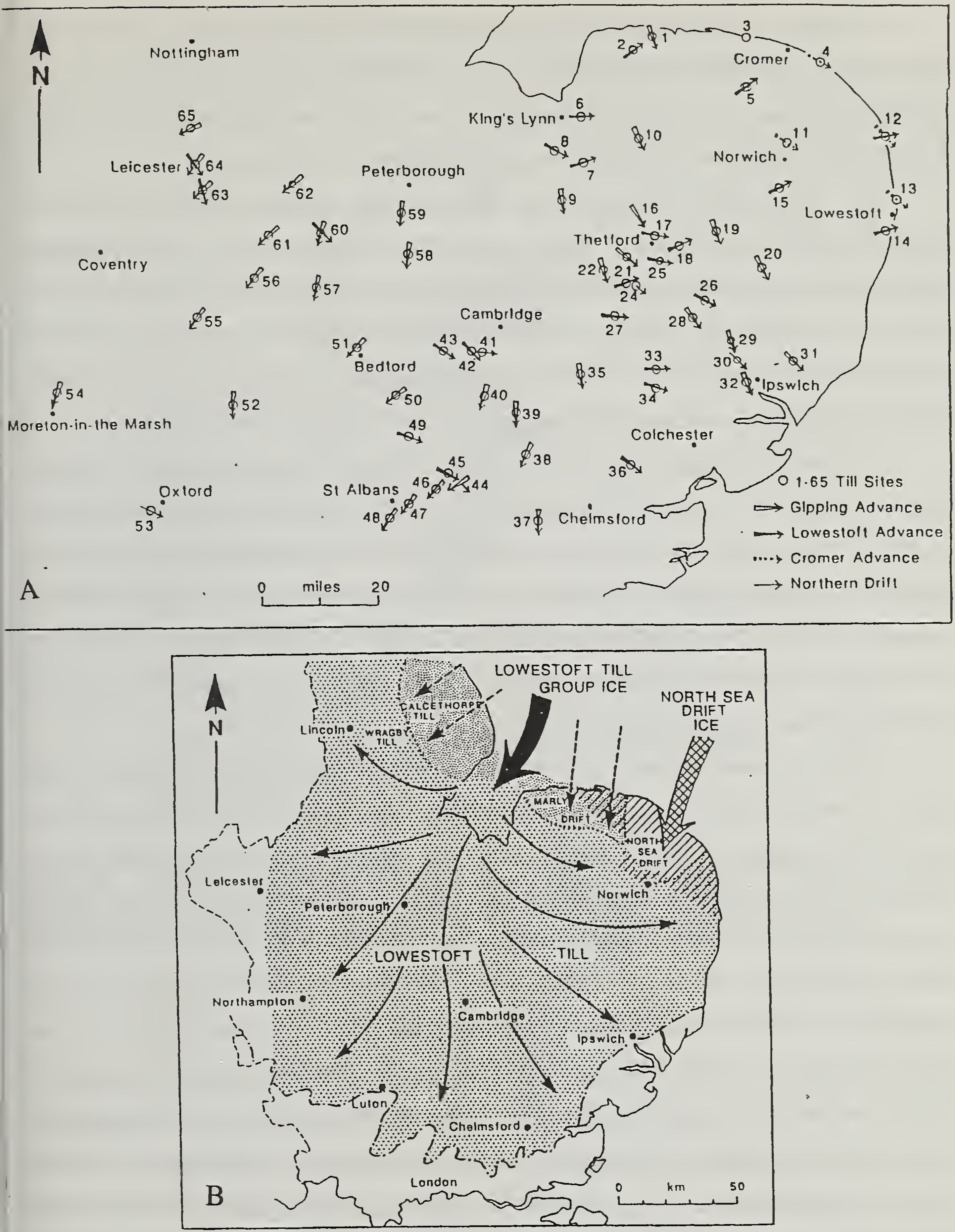


Fig. 9. Maps showing local ice movements during the Anglian glaciation **A)** after West and Donner (1956) and **B)** after Perrin *et al.* (1979).

In contrast to the rather complicated ice flow-path directions of the Lowestoft Till, almost all workers (Table 16) agree that the Marly Drift/Gipping Till ice came from the N or near N (Fig. 9b) and entered Norfolk directly over the chalk outcrop in north and north-west Norfolk (West and Donner 1956; Perrin *et al.*,1979; Ehlers *et al.* 1987).

Past work therefore indicates three ice flow-path directions within Norfolk and Suffolk, initially to the SE and E, then to the ENE and finally to the S. This study has identified three 'Lowestoft Till' group R clusters deposited in the order: Cluster R6 (CBC), Cluster R12 (MDv) and Cluster 1 (MD); the upper and lower member considered equivalents of the Lowestoft Till and Marly Drift respectively. Accepting this, the ice flow-path directions for the upper and lower members are defined by the discussion above.

The middle stratigraphic unit Cluster R12 (MDv) has a fine sand fraction magnetic character much more strongly differentiated from Cluster R1 (MD) than from R6 (CBC). Similarly, Ehlers *et al.* (1991) recognize an older Marly Drift characterised by its Jurassic component, a characteristic of Lowestoft Till but not of Marly Drift. These links to Lowestoft Till, and the stratigraphic position of Cluster R12 (MDv) suggest equivalence with the older Marly Drift of Ehlers *et al.* (1991), which can also be related to the changes in ice flow-path direction (Fig. 10).

The relationship between Clusters R12 (MDv) and R6 (CBC) could stem from effects in both the source area and the depositional site. For example, differentiation in source area magnetic character might derive from different ice flow-paths with superimposition at ice convergence (Madgett and Catt 1978), or from changes in glacier dynamics with time (Eyles *et al.* 1982). Alternatively, different stages in the erosion of the source material might have generated sediment with diagnostic magnetic minerals that was maintained at different levels within the glacier (Shilts 1976, Dreimanis 1989). In the depositional area the stratigraphic order of the tills could reflect any of the above forms of layered ice sheet, or subsequent deposition from successive lobes from differing distal sources. The clear differentiation of fine sand fraction magnetic character in these till facies, with no identified local source of multi-domain magnetite, probably indicates distal differentiation. The lack of sharp stratigraphic differentiation for the middle unit might represent incorporation and mixing of drift facies during either transportation or deposition.

The alternative explanation is that the layering represents different modes of deposition forming flow, melt-out, lodgement and deformational tills. However, the

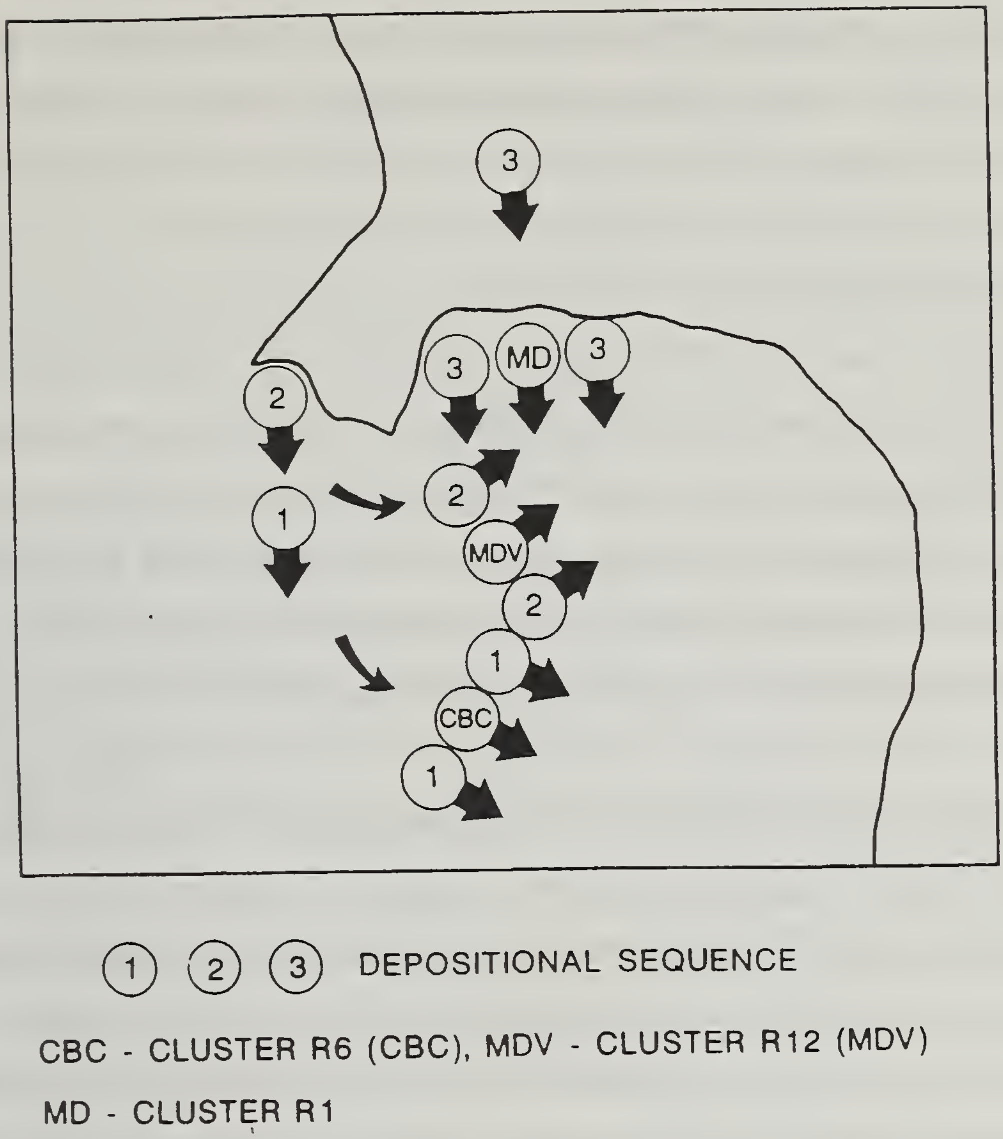

3
3
MD
3
2
2
1
MDV
2
1
CBC
1
① ② ③ DEPOSITIONAL SEQUENCE
CBC - CLUSTER R6 (CBC), MDV - CLUSTER R12 (MDV)
MD - CLUSTER R1

Fig. 10. Iceflow directions in relation to the stratigraphic sequence of the Lowestoft Till group after West and Donner (1956), Ehlers *et al.* (1987), Rose (1992) and this study.

similarity of the gross lithology of Clusters R1 (MD), R6 (CBC) and R12 (MDv) (Corbett 2001a) suggests a common depositional mode. In particular, the upper part of the sequence lacks differential sorting which is indicative of flow tills. Moreover, in the lower part of the sequence, the till lacks sediment incorporated locally from below; this would not be usual in a deformation till. The depositional mode therefore appears to have been of melt-out or lodgement type.

North Sea Drift Formation

There is almost complete agreement that the distal direction of North Sea Drift ice flow was from the NE or N (Table 16; Fig. 9b), the most obvious sediment source area being the floor of the North Sea. The results of this study confirm these findings. The magnetic character of the fine sand fractions in the R Variable-derived equivalents of the First and Second Cromer Tills (Clusters R2 (NSD) and R5 (BR/NSD) respectively) and the Breckland chalk-sand plateau drift includes a relatively low concentration of various magnetic minerals including haematite and goethite. This magnetic character indicates the Yarmouth Road Beds of the North Sea basin as a principal source of the fine sand (Fig. 7A).

The local direction of North Sea Drift ice flow varied with the succeeding till members of the North Sea Drift Group becoming progressively more westerly. This trend may represent a progressively stronger interaction with the British east coast ice sheet. For the First Cromer Till most workers give the same local direction of ice flow as its distal flow direction (i.e. from the NE (Table 16), for the Second Cromer Till from the NW and for the third from the NW or W.

The differences in direction of the ice paths that deposited the First and Second Cromer Tills are reflected in the marked differences in the total carbonate content of Clusters R2 (NSD) and Cluster R5 (BR/NSD) (see Corbett 2001a). This difference may reflect the relative distances travelled across the Chalk outcrop (see also Corbett 1996). Alternatively, the First Cromer Till ice may have over-ridden and removed superficial deposits from the surface of the Chalk outcrop north of the present north Norfolk coastline. The ice of the Second Cromer Till could then have eroded the exposed chalk surface. This interpretation would require a more northerly ice flow movement for the First Cromer Till. However, Cluster R5 (BR/NSD; equivalent of the Second Cromer Till) has the higher ratio of coarse to fine carbonate (CTOFINE, Table 10). This could have been derived only by ice that crossed beds of harder chalk that occur in the western parts of the chalk outcrop.

Overall the findings of the present study agree broadly with the earlier work, indicating a westward rotation in the ice flow direction during deposition of the North Sea Drifts.

Interactions between North Sea Drift and Lowestoft Till Ice

Overlying the solid chalk and a layer of chalk rubble on the Breckland plateau Corbett (1973) recognised an unsorted structureless drift, possibly a till. On and nearby valley side slopes, however, thinner more chalky drifts occurred with structures indicating periglacial mixing (Corbett 1973). At that time these drifts were considered to be peculiar to the unique Breckland landscape; however, the results of this study change that interpretation. The more widespread plateau drifts are linked in this study to Cluster R5 (BR/NSD), which is equivalent to the Second Cromer Till at Overstrand (Corbett 2001a) and is also found at depth near Swanton Novers (Corbett 2001b). Further evidence that North Sea Drift ice once spread so far S and W is a brown and sandy diamicton at Knettishall (Fig. 1) part of Cluster R2(NSD) of Corbett (2001b) and classed as an equivalent to the First or Third Cromer Till. These findings extend westward the numerous recordings of the North Sea Drifts in or near the Waveney Valley.

Comparisons of the magnetic character of the Breckland coversand with the fine sand fraction in the underlying chalky drift are inconclusive. Their MDF values are significantly different at the 95% confidence level (Table 12), and their magnetic remanence curves are very similar (Fig. 6D), but the concentrations of magnetic minerals are not significantly different (Table 14).

A second Breckland drift facies (Cluster R3 (BRv)) was also recognized near the plateau perimeter and at Knettishall (Corbett 2001a). This facies may be a product of interaction between the clay-enriched base of the Lowestoft Till ice with either *in situ* First or Third Cromer Tills, or their ice. These Breckland and North Sea Drift facies also occur on the lower slopes in transects at Bunwell and Flordon (Fig. 1; Corbett 2001b). At Bunwell they may be an inclusion in the Chalky Boulderclay (Corbett 2001b). At Flordon, however, they maybe *in situ* (Corbett 2001b) and their sharp (upslope) vertical boundary with Cluster R6 (CBC) may be the edge of the trough, a feature similar to that cut into the lower drifts, including the North Sea Drift, at Knettishall.

A final point regarding interactions between ice sheets is the occurrence of 'Lowestoft Till' group R cluster facies at Mundesley and West Runton (Fig. 1). Earlier, both Baden-Powell (1948) and West and Donner (1956) had concluded that the final direction of movement of the Lowestoft Till ice was to the ENE. It is therefore possible that this ice reached the present coast at Mundesley, influencing locally the lithology of the Second Cromer Till. However, field surveying and deep borings by Cox and Nickless (1972) identified a sharp north-south boundary, marked by intervening outwash, northward from Norwich, with Lowestoft Till to the west and a weathered North Sea Drift representative to the east.

The direction of flow-path for the Second Cromer Till is given by most workers as from the NW. This flow direction and the even more westerly direction of the Third Cromer Till ice has been interpreted as an increasing reaction to Lowestoft Till ice coming down the east coast (Hart 1987). If this reaction also involved some mixing of sediment load it could explain inclusions of the Lowestoft Till group in the Second Cromer Till. It seems, therefore, possible that the two ice flow paths (those of the Lowestoft Till and the Second Cromer Till), crossed similar Jurassic sediment outcrops, perhaps in the area of the Sole Pit High on the floor of the North Sea (but see below). These results, although based on only a few samples are consistent with the recent findings of Moorlock *et al.* (2000a; 2000b) who noted the similarity in mineralogical and grain size data between the Second Cromer Till (their Walcott Diamicton Member) and the Lowestoft Till. These authors interpret the presence of certain Jurassic palynomorphs to indicate derivation from Jurassic bedrock erosion in eastern England rather than secondary derivation from the floor of the North Sea (Moorlock *et al.* 2000b). There is currently debate about whether the mineralogical similarities between the Second Cromer Till and the Lowestoft Till demonstrate stratigraphic equivalence, as claimed by Moorlock *et al.* (2000a) and Hamblin *et al.*, (2000), or otherwise (see e.g. Banham *et al.*, 2001). Further work is currently directed at resolving this issue.

The final 'Marly Drift' advance of the Lowestoft Till ice was from the N, an event that formed the Cromer ridge (best seen near Cromer, Fig. 1) and the disturbed sequence of beds termed the Contorted Drift (Banham *et al.* 1975; Banham and West 1977). The Contorted Drift contains remnant bodies of Marly Drift (Ehlers *et al.* 1991), perhaps lumps of hard chalk broken up by tectonic shear and streaked into chalk-rich laminae (Hart 1987) producing a North Sea Drift type of Marly Drift (Banham *et al.* 1975). Inclusions of Marly Drift have also been identified near the top of the cliff sections from Mundesley northwards (Lunkka 1994).

CONCLUSIONS

1. The magnetic character of the fine sand fraction in the Ratio/Magnetism-derived drift facies of Corbett (2001a) is sharply discriminating. This is probably because it reflects in part the distal origin of the sediments; possibly at distances of up to hundreds of kilometres from the site of till deposition.

   More generally, Measured Variable classification (Corbettt (2001a) reflects local sediment input whereas Ratio/Magnetism Variable classification reflects distal input. Only the latter, in the 'Lowestoft Till' group of drift facies, occur in a stratigraphic pattern. This suggests that use of gross lithology variability (M Variables) for stratigraphic interpretation can be misleading (see also Corbett 2001b).

2. The spatial pattern of the R Variable-derived drift facies shows that an equivalent of the North Sea Drift group occurs in north Suffolk, i.e. the First or Third Cromer Till at Knettishall. In the 'Lowestoft Till' group the R Variable-derived drift facies equated with the Marly Drift occur as a thick surface layer over most of the Chalky Boulder Clay plateau in Norfolk and north Suffolk. It forms the upper unit of a three unit stratigraphic sequence, the lower one equated with the Lowestoft Till *sensu stricto* of Baden-Powell (1948), the middle unit containing both Lowestoft Till and a Lowestoft Till facies of the Marly Drift.

3. The distal fine sediment sources of the glaciers of the North Sea Drift and Lowestoft Till groups are differentiated by the magnetic character of their fine sand fractions. The R Variable-derived drift facies of the 'North Sea Drift' group are clearly associated with the Yarmouth Road Beds and characterised by a wide range of ‘hard’ magnetic minerals such as goethite and haematite, but in low concentration. In contrast, the 'Lowestoft Till' group is characterised by a narrower range of magnetic minerals but in higher concentration, the character being dominated by varying proportions of magnetite. The source of the sand fraction could be in part the Shouldham Sands in west Norfolk and the Jurassic sandstones in east Yorkshire, but there is an additional multi-domain magnetite

component derived probably from igneous rock in northern England or eastern Scotland. In terms of local sources for the R Variable-derived drift facies of the 'North Sea Drift' group, the equivalent of the First Cromer Till, i.e. Cluster R2 (NSD), is distinguished from the Second Cromer Till, i.e. Cluster R5 (BR/NSD) by having less total carbonate and a lower ratio of coarse to fine carbonate. Both these features may be associated with a more easterly ice path. For the 'Lowestoft Till' group there is little differentiation for either total carbonate or the ratio of fine to coarse carbonate and these features indicate common local sources and mixing. Moreover, the Lower Cretaceous Sands in west Norfolk seem to have made little or no significant contribution to the 'Lowestoft Till' group.

4. The results of this study broadly agree with earlier work regarding the directions of ice flow. The distal flow direction for members of the 'North Sea Drift' group was from the NE, from the floor of the North Sea and the ice advanced as far south as north Suffolk. For the 'Lowestoft Till' group, the ice flow was broadly SE and then S through eastern England. Variations in local ice flow directions for both groups of drift facies were probably due to interaction between and within the major ice flows.

   Interaction between ice flows and/or their pre-existing deposits suggests a possible origin of one of the Breckland drift facies (Cluster R5) where inclusions of North Sea Drift equivalents occur at depth within a local stratigraphy of 'Lowestoft Till' group facies. Similarly in northeast Norfolk, inclusions of the 'Lowestoft Till' group occur in the Second Cromer Till, possibly resulting from interaction between ice flows. This finding supports those of Moorlock *et al.*, (2000a; 2000b), although they favour direct stratigraphic equivalence of the two tills.

Events of the Lowestoft Till glaciation in East Anglia

A. Ice from the Wash area flowed to the SE and E cresting and eroding the chalk escarpment. On the East Anglian plateau, Chalky Boulderclay was deposited. The final stages of deposition may have incorporated in the surface of the Chalky Boulderclay a variant of the Marly Drift with a Jurassic component and with a distinctive magnetic character in its fine sand fraction.

B. To the east of Norwich in south Norfolk and Suffolk, Lowestoft Till ice over-rode either North Sea Drifts or their ice to give the stratigraphic sequence of Lowestoft Till over North Sea Drift seen at Corton, Knettishall and possibly Flordon.

C. Lowestoft Till ice flowed directly onto the present land area of Norfolk from the north, mantling the Chalky Boulder Clay over the central plateau with a Marly Drift free of Jurassic material. The early stages of this invasion if ice may have mixed Chalky Boulder Clay with basal debris rich in magnetite to produce a Marly Drift with Jurassic fossils.

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PILOT STUDY IN DIFFERENTIATING NORTH NORFOLK GLACIAL SEDIMENTS USING MINERAL MAGNETIC DATA

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*deceased

ABSTRACT

Pilot mineral magnetic data from the fine-sand fraction of glacial sediments from north Norfolk suggest that two magnetic parameters, the Absolute Saturation Isothermal Remanent Magnetism (A1000 mT) and the Median Destructive Field (MDF) may help discriminate glacial sediments of Anglian and Devensian age. Samples are most obviously separated by the large range in A1000 mT values. One group of glacial sediments have A1000 mT values between 170-340, implying a high concentration of magnetic minerals. MDF variability is low in this group, around 40-50, probably indicating the presence of easily magnetised magnetite. This group might represent a magnetically distinct Devensian 'Hunstanton Till'. The second group of glacial sediments has A1000 mT values mostly below 40, implying low concentrations of magnetic minerals, but with variable MDF values (45-70). This second group has A1000 mT and MDF values within error of previously published data for Anglian tills elsewhere in Norfolk. In some localities, particularly in the Cley-Blakeney-Warham area, these magnetically distinct sediments are in close juxtaposition. The identification of glacial sediments with 'Hunstanton Till' and 'Anglian till' magnetic character supports earlier work which suggested that at least two groups of glacial sediments are present on the north Norfolk coast. A more complete study of glacial sediments in north Norfolk, using the techniques outlined here along with traditional sedimentological and mineralogical data, is needed to confirm these initial findings and extend the geographic coverage.

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INTRODUCTION

Before his death in May 2000, Brian Funnell had been working on various aspects of the Quaternary geology of the low-lying north Norfolk coastline between Salthouse and Holme-next-the-Sea. In the 1990s Brian had reinvigorated his long-standing interest in this area as part of the Natural Environment Research Council's Land Ocean Interaction Study (LOIS). He had been working with others on the evolution of the Holocene north Norfolk coastline (see overview in Andrews *et al.*, 2000a) as part of the Land Ocean Evolution Perspectives Study (LOEPS) component of LOIS (Shennan and Andrews 2000). Brian was particularly interested in the geology of the eastern end of the study area around Blakeney Spit (Funnell *et al.*, 2000). His fieldwork in this area included a close look at the glacial 'eyes'- hillocks of till and glaciofluvial sand and gravel - that break through the Holocene cover between Cley and Salthouse (Fig. 1).

Although a chalky till of presumed Anglian age had been discovered at Cley Eye (TG 052451) in the 1980s (Funnell pers. comm. 1990 in England and Lee 1991), by the mid 1990s as part of his LOIS work, Brian was less certain that the Cley Eye sediments were all of Anglian age. The 1884 Geological Survey mapping of the 'eyes' was equivocal (Woodward 1884), with Whitaker and Jukes-Brown (1899) noting that Woodward had been unable to separate 'younger' glacial sediments from the 'Contorted Drift Series' (now known to be Anglian in age) in the area of Sheet 68 NW and SW. Today it is well known that presumed Devensian till (Hunstanton Till; see England and Lee 1991) crops out just 6 to 15km to the west of Cley Eye at Morston (Gale *et al.* 1988) and Holkham respectively (Madgett and Catt 1978). It is thus possible that the 'eye' deposits are similarly of Devensian age (see Fig. 1).

In the late 1990s Brian Funnell invited William Corbett to examine the mineralogical, grain size and mineral magnetic character of some of these north Norfolk glacial sediments. It was hoped that comparison of their magnetic properties with data from known Anglian deposits elsewhere in Norfolk (Corbett 1996; 2001a; 2001b; 2002) might help distinguish between Anglian and Devensian sediments. In the following report we outline the results of this preliminary study.

SAMPLES AND METHODS

Sixteen samples were studied, collected either from outcrop or from archived core. Sample localities, grid references, depths relative to Ordnance Datum (OD) and lithologies are given in Table 1 and Fig. 1. Analyses of till samples from Cley Eye were

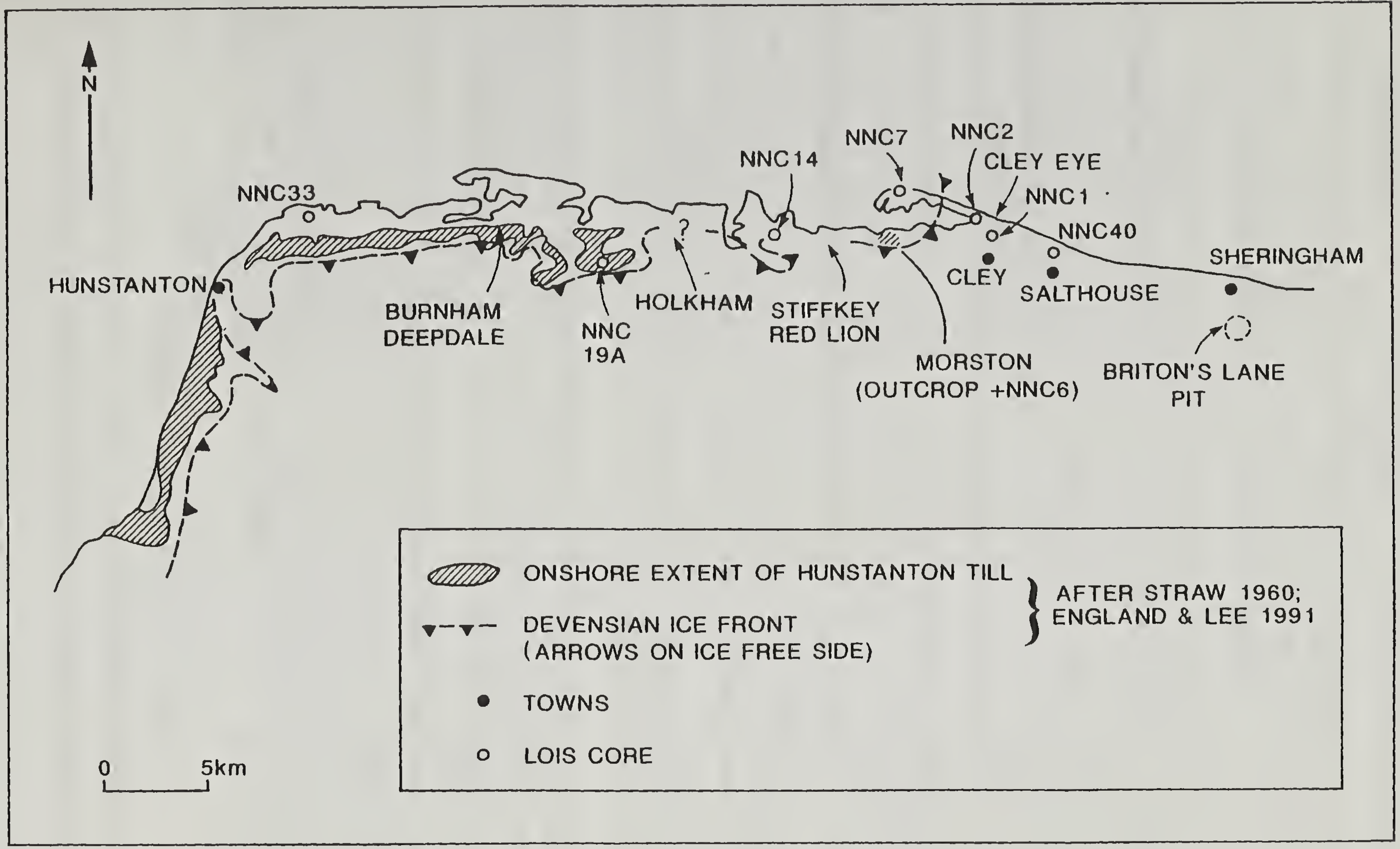


Fig. 1. Location of the main sample sites. Onshore extent of the Hunstanton Till and presumed Devensian ice front (after Straw 1960; England and Lee 1991) are also shown. The LOIS cores are prefixed NNC (North Norfolk Coast).

Table 1. Sample locality and lithology data (see also Fig. 1).

Sample No.	Locality/Core/Grid Ref.	Elevation (m OD)	Lithology
1*	Briton's Lane Pit, sample 1 (TG 1689 4144)	c.+64	Blue-grey till
2*	Briton's Lane Pit, sample 2 (TG 1695 4149)	c.+62	Chalky till, brown
3	Cley Eye (TG 052 452)	+3 to +4	Till
4	Burnham Overy (NNC 19A) (TF 8581 4564)	-7	Sand, silty with chalk pebbles
5	Cley Eye (TG 052 452)	+3 to +4	Till
6	Holme (NNC 33) (TF 7073 4428)	-4.5	Silty-clay, firm, medium brown with chalk pebbles
7	Cley Marsh (NNC 1) (TG 0391 4462)	-9 to -10	Sand
8	Cley Marsh(NNC 1) (TG 0391 4462)	-11 to -12	Sand
9	Blakeney Spit (near Blakeney Eye) (NNC 2) (TG0336 4577)	-5.5 to -6	Silt with chalk and flint pebbles
10	Morston Marsh (NNC 6) (TF 9996 4457	-1 to -1.5	Silty-clay, firm, red-brown, flint and chalk pebbles
11	Blakeney Point (seaward beach) (NNC 7) (TG 9987 4671)	-10.5 to -11.5	Sand with small chalk pebbles
12	Warham Marsh (NNC 14) (TG 9484 4430)	-15 to -15.8	Sand with small flint pebbles
13	Salthouse Marsh (NNC 40) (TG 8140 4400)	-9 to -10	Sand with chalk and flint granules
14	Salthouse Marsh (NNC 40) (TG 8140 4400)	-11 to -12	Sand with chalk and flint granules
15	Stiffkey Red Lion car park (TF 9695 4325)	c. +10	Chalky sediment above prominent red clay unit
16	Stiffkey Red Lion car park (TF 9695 4325)	c. +10	Silty-clay from red clay unit. Sample contains silt, sand and chalky flecks.

* sampled by A. J. Read, 31 March 1993

Graphic logs of all the NNC cores (except NNC 33) are in Andrews *et al.* (2000a).

followed up with further samples, mostly from recently recovered glaciofluvial sediments in the bases of many of the LOEPS boreholes (Andrews *et al.*, 2000a; Funnell *et al.*, 2000) between Salthouse and Holme-next-the-Sea. Two samples (15 and 16; Table 1) were taken from chalk-rich diamict exposed in a face beside the car park of the Red Lion Public House in Stiffkey Village. Two till samples (1 and 2) were collected by Adrian Read from Briton's Lane Gravel Pit at Beeston Regis near Sheringham, part of the Cromer Ridge complex. These till samples came from below the main gravel deposits and would be classed by most workers as Anglian.

Mineralogical, grain size and magnetic measurements were carried out as described in Corbett (2001a; 2002). The magnetic parameters were measured on the non-carbonate fine-sand (63-250 μm) fraction of the samples. Details of the decalcification and sieving procedures are given in Corbett (2001a). As two of the non-carbonate fine-sand fraction magnetic parameters (A1000 mT and MDF) appear to be important determinants (Corbett (2002), the magnetic measurement methods are described briefly here. Magnetic remanence (a measure of the magnetism retained after a sample is removed from a magnetic field of known strength) was induced by field strengths of 10, 40, 100, 300 and 1000 milli-Tesla (mT). These remanence measurements were converted to a standard (percentage) scale by using the 1000 mT value (the Saturation Isothermal Remanent Magnetism (SIRM)) as 100% and scaling the lesser remanence values to this (Table 2). The 1000 mT value was also made absolute (A1000 mT) by taking account of the sample mass to provide a measure of the concentration of magnetic mineral grains. The Median Destructive Field (MDF), which quantifies the magnetic character of the sample for the lower field strengths, was derived by determining the field strength necessary to give a 50% remanence value, this being equal to the applied field which would overprint the 'softest' 50% of the remanence. (The term 'soft' here indicates remanence due to grains whose magnetic domains may be relatively easily re-ordered or overprinted when the sample is exposed to a new magnetic field).

RESULTS AND INTERPETATION

The data available are given in Tables 2 and 3. The most informative use of the data is derived by cross plotting the mean A1000 mT values against the mean MDF values (Fig. 2). As the magnetic measurements were made on the non-carbonate fine-sand (63-250 μm) fraction, any data variability due to grain size effects should be eliminated (see also Walden *et al.*, 1995). The data are thus directly comparable with those derived from

Table 2. Mineral magnetic data determined on the non-carbonate fine-sand fraction.

	Magnetic Parameters						
Sample	**10 mT**	**40 mT**	**100 mT**	**300 mT**	**1000 mT**	**A1000 mT**	**MDF**
1. Briton's Lane (Blue-grey till)	31.9 7.0	36.7 39.5	64.0 68.8	84.9 77.5	100 100	22.6 24.5	63 56
2. Briton's Lane (Chalky till, brown)	8.0	45.0	78.0	93.7	100	29.2	46
3. Cley Eye, till	28.6	50.8	88.0	99.5	100	242.8	39
4. NNC 19A, sand (Burnham Overy)	38.1	44.1	79.4	95.1	100	37.5	46
5. Cley Eye, till	5.9 3.2	44.1 44.4	83.4 83.6	95.6 96.2	100 100	261.1 274.4	46 45
6. NNC 33, silty-clay (Holme)	29.1	45.4	83.7	97.4	100	235.9	45
7. NNC 1, sand (Cley)	2.3	31.8	79.1	80.6	100	33.5	49
8. NNC 1, sand (Cley)	2.2	21.4	60.3	71.6	100	29.9	67
9. NNC 2, silt (Blakeney)	3.0	21.3	68.3	76.2	100	15.0	57
10. NNC 6, mud (Morston)	4.0	42.2	80.2	93.8	100	173.3	50
11. NNC 7, mud (Blakeney)	3.4	48.0	76.1	86.1	100	331.6	41
12. NNC 14, sand (Warham)	3.6	36.7	89.3	89.3	100	14.7	46
13. NNC 40, sand (Salthouse)	3.2	46.4	79.8	92.1	100	246.6	42
14. NNC 40, sand (Salthouse)	3.4	48.6	81.2	91.4	100	222.9	41
15. Stiffkey, chalky sediment	4.4	41.1	83.3	84.4	100	62.1	44
16. Stiffkey, red clay unit	34.3	39.7	85.0	93.1	100	122.5	58

Table 3. Particle size and carbonate content data for selected samples

	Particle Size (µm) (Total)					**Particle Size (µm) (Carbonate)**				**Particle Size (µm) (non Carb)**			
Sample	**2000 - 500**	**500-250**	**250-63**	**<63**	**TC**	**>500**	**500-250**	**250 -63**	**<63**	**>500**	**500 -250**	**250 -63**	**<63**
1. Briton's Lane (Blue-grey till)	3.5	6.8	34.6	55.1	7.5	0.2	0.1	0.1	7.2	3.3	6.7	34.6	47.9
2. Briton's Lane (Chalky till, brown)	0.4	0.5	2.0	97.0	74.2	0.0	0.0	0.1	74.0	0.4	0.5	1.9	23.0
3. Cley Eye, till	5.3	5.1	23.2	66.5	9.5	0.7	0.2	1.3	7.4	4.6	4.9	21.9	59.0
4. NNC 19A, silt/sand (Burnham Overy)	15.1	15.1	31.1	38.6	26.3	5.0	0.3	1.1	19.9	10.1	14.8	30.0	18.8
6. Cley Eye, till	9.8	5.0	28.5	56.7	10.4	1.1	0.2	1.5	7.6	8.7	4.8	26.9	49.2
7. NNC 33, silty-clay (Holme)	7.4	8.0	29.2	55.4	11.6	1.9	0.4	1.2	8.1	5.5	7.6	28.1	47.3

Values represent wt %.   TC = total wt% calcium carbonate

Anglian tills and potential sand sources to tills in Norfolk and Suffolk (Corbett 2002, fig. 7). The mean values and regression lines from Corbett (2002) are shown in Figure 2 to aid comparison.

The data in Figure 2 show a large range in A1000 mT values. One group of glacial sediments have A1000 mT values between 170-340; they include samples 10 (Morston), 13 and 14 (Salthouse), 3 and 5 (Cley Eye) 6 (Holme) and 11 (Blakeney). These high A1000 mT values imply a high concentration of magnetic minerals. MDF variability is low in this group of samples, around 40-50 (Fig. 2), probably indicating the presence of an easily-magnetised 'soft' IRM, such as magnetite.

The second group of glacial sediments in Figure 2 have A1000 mT values below 60, and mostly below 40, including samples 1 and 2 (Briton's Lane Gravel Pit, Cromer Ridge), 4 (Burnham Overy), 7 and 8 (Cley), 9 (Blakeney) and 12 (Warham). These samples therefore appear to have low concentrations of magnetic minerals, but with variable mean MDF values (45-70). The higher MDF values probably indicate the increased presence of 'hard' remanence magnetic materials, such as haematite and goethite.

A logical conclusion that might be drawn from Figure 2 is that two groups of glacial sediment have been sampled. The first group, that includes the samples from Cley Eye, has high A1000 mT values and relatively low MDF values, quite distinct from any of the Anglian tills sampled by Corbett (2002). This group may represent a magnetically distinct 'Hunstanton Till'. The second group has magnetic characteristics that are essentially indistinguishable from Anglian North Sea Drift and Marly Drift facies of Corbett (2002). The samples from Briton's Lane Gravel Pit are part of this second group, suggesting a genetic link with the North Sea Drift and/or Marly Drift facies of Corbett (2002).

The magnetic data from samples 15 and 16 (Stiffkey Red Lion Public House car park, Table 1) are more difficult to interpret and deserve specific discussion. Sample 16 comes from a prominent unit of red clay that rests on top of a highly fractured chalk mass. Sample 15 was taken from a rubbly weathered chalk-rich diamicton above the red clay unit. The age and genesis of these sediments is not known with certainty. The red clay unit is in places silty and sandy. It contains flecks, granules and rounded pebbles of chalk, and also flint and erratic pebbles.

The 'redness' (field colour Munsell 5YR 4/4) of the red clay unit is certainly similar to other outcrops of the 'Hunstanton Till' and Mr. J. A. Lee (Royal Holloway)

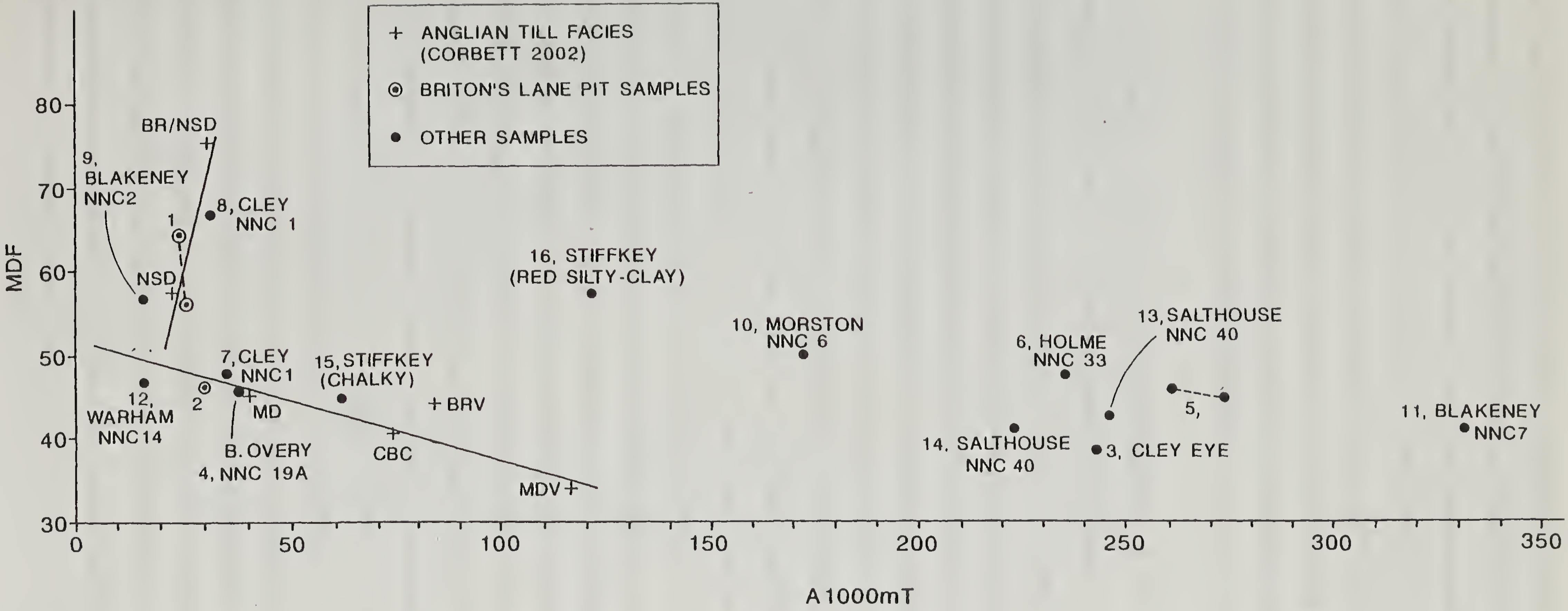


Fig. 2. Plot of MDF and A1000mT data from Table 2. The data are compared with mean values and regression lines for CBC = Chalky Boulderclay; MD = Marly Drift; NSD = North Sea Drift; BR = Breckland Drift; MDV = Marly Drift Variant; BRV = Breckland Drift Variant, the major R-derived Anglian drift facies of Corbett (2002). The LOIS cores are prefixed NNC (North Norfolk Coast).

has advised us that the ratio of opaque to non-opaque heavy minerals from this unit showed similarities with analyses of samples of 'Hunstanton Till' taken elsewhere. The compositional range of far-travelled erratics is also consistent with those found elsewhere in the Hunstanton Till (P.G. Hoare pers. comm. 2001). On this basis the red clay unit and overlying chalk-rich diamicton are interpreted as Devensian deposits. The chalky materials are probably locally derived, either from chalk bedrock or possibly from Anglian chalk-rich diamicts that occur in the area. Indeed Dr. P.G. Hoare (pers. comm. 2001) considers the chalk mass below the red clay unit to be glacially sheared *in situ* Chalk bedrock.

The chalk-rich sample (15) has magnetic characteristics similar to those of Corbett's Anglian Chalky Boulderclay grouping (Fig. 2; Corbett 2002). This result is consistent with the chalky material being derived from either bedrock or Anglian tills but does not help characterise the unit as either Anglian or Devensian. Sample 16, a silty-clay from the red clay unit, has an A1000 mT value intermediate between the groups of samples with 'Anglian' and 'Hunstanton Till' character (Fig. 2). Although the A1000 mT value for sample 16 is similar to the mean value for Corbett's Marly Drift variant (MDV) facies (Corbett 2002; Fig. 2), its MDF value is much higher (Fig. 2). These rather unusual magnetic characteristics do not help assign an unequivocal age to the deposit. More detailed mineralogical and magnetic and work on a bigger sample set is needed to help better characterisation of the Stiffkey Red Lion sediments.

Only three of the samples distinguished as 'Hunstanton Till' on the basis of magnetic data have grain-size data (i.e. samples 3 and 5 (Cley Eye) and 6 (Holme) in Table 3). However, the grain-size distribution data are not diagnostic, in that they are similar to the Hunstanton Till grain size data presented by Gale *et al.* (1988), but also to Anglian tills in Norfolk (see for example Corbett 2001a, fig. 8). Direct comparison between Hunstanton Till grain-size data such as that presented here and in Gale *et al.* (1988), or Madgett and Catt (1978), are in any case complicated because of the potentially variable effects of weathering and pedogenesis at each site.

The total carbonate data in samples 3, 5 and 6 (Table 3) are between 9.5 and 11.6%, just less than the mean value of 13.1% for the Skipsea Till of eastern England (equivalent to the Hunstanton Till) given by Madgett and Catt (1978). Most of the Anglian tills studied by Corbett (2001a) have either significantly higher total carbonate contents (e.g. his Chalky Boulderclay and Marly Drift facies) or lower total carbonate contents (e.g. some of the North Sea Drifts; Corbett 2001a, table 4). It is thus possible that total carbonate content, combined with magnetic data, might be a reasonable discriminator of the Hunstanton Till. Certainly, samples 1 and 2 from Briton's Lane Gravel Pit have either higher or lower total carbonate values than those identified as possible Hunstanton Till samples (samples 3, 5 and 6). Clearly, however, a larger sample set is needed, and care in sample selection is essential. Many authors point out that subaerial decalcification of the Hunstanton Till is common (e.g. Gale *et al.*,1988; England and Lee 1991), while incorporation of chalky masses into the till (e.g. the Stiffkey Red Lion outcrop) is equally possible.

DISCUSSION

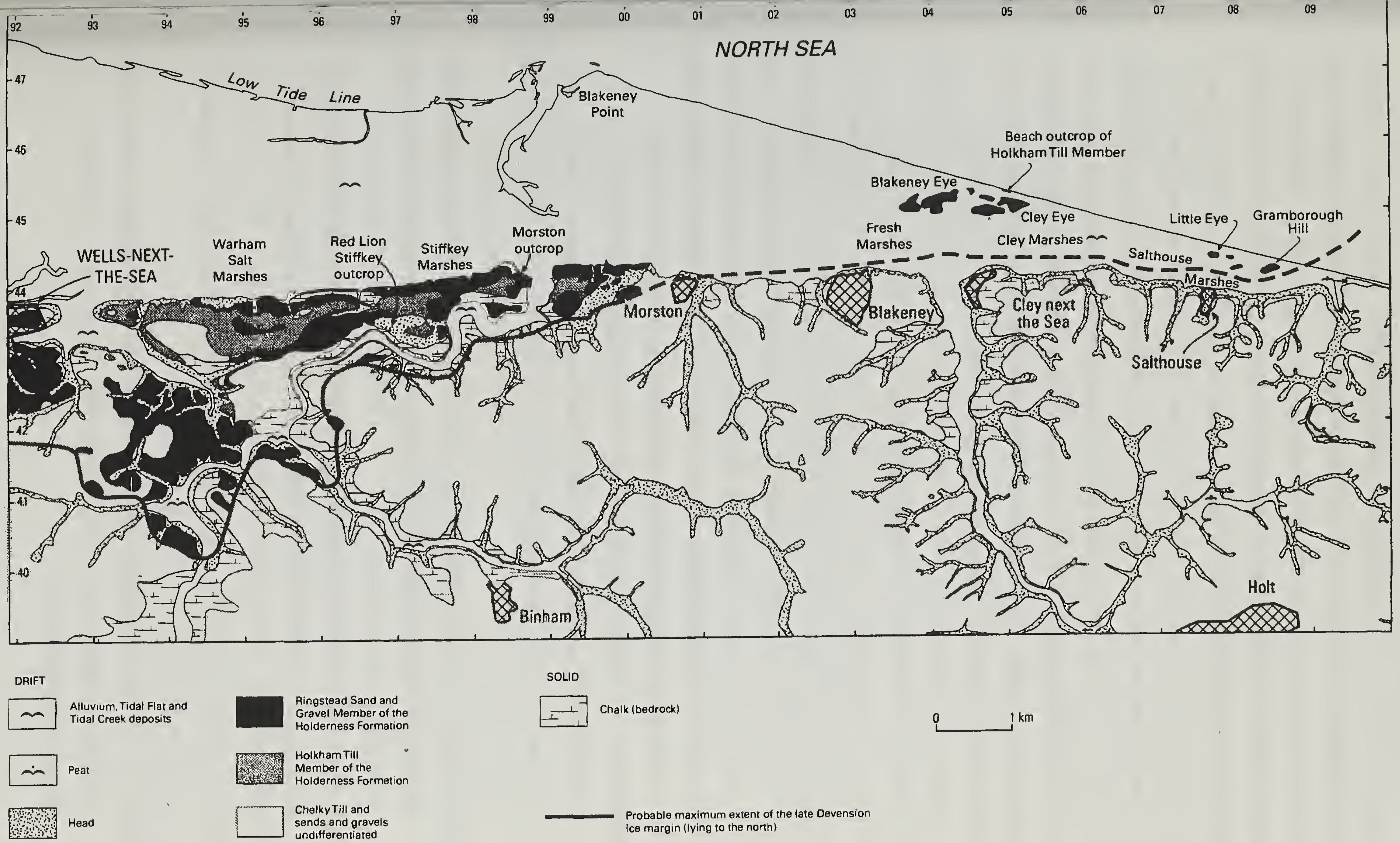
If the interpretations of these pilot data are correct, they support earlier work which suggested that at least two groups of glacial sediments are present on the north Norfolk coast between Morston to Hunstanton: a younger Hunstanton Till of Devensian age, and an older Anglian till (Straw 1960). The work by Gale *et al.* (1988) at Morston (TF 896436) is most convincing, where '...till of presumed last glacial age has been found overlying older till'. Our results suggest that Devensian Till and associated glaciofluvial sediments are also present further east of Morston in the Cley-Blakeney area; here, as at Morston, Devensian and Anglian glacial sediments are in close juxtaposition. For example, at Cley Eye the sediments at +3 to +4 m OD show magnetic characteristics of 'Hunstanton Till', while only 500 m to the south, sediments in core NNC 1 at -9 to -12 m OD show magnetic characteristics most similar to Anglian till studied by Corbett (2002). Superimposition of two tills was also implied by Whitaker and Jukes-Brown (1899) in a pit 1 km south of Burnham Deepdale (see also England and Lee 1991). Although this pit no longer exists, a LOIS core approximately 1 km to the north (NNC 27; TF 8069 4478) confirms the presence of glaciofluvial sediments below -2 m OD in this area. These sediments are very chalky toward the base of the core at -8.72 m OD and further work could be aimed at establishing whether they represent the deposits of more than one glaciation.

The identification of glaciofluvial sands and gravels with 'Anglian magnetic character' (samples 4 (Burnham Overy NNC 19A), 7 and 8 (Cley NNC 1), 9 (Blakeney NNC 2), and 12 (Warham NNC 14)) near the base of a major E-W trending trough or valley feature beneath the Holocene sediments of the north Norfolk coast (Chroston *et al.* 1999) is potentially important. Their 'Anglian magnetic character' is the first tentative evidence that the trough represents a pre-Devensian feature (Funnell *et al.*, 2000) and casts doubt on the suggestion that the trough was initially cut by drainage from the southern margin of the Devensian glacier (Funnell *et al.*, 2000; Andrews *et al.*, 2000b). Although samples 11, 13 and 14 (Blakeney and Salthouse area) were all sampled below -9m and have 'Hunstanton Till' magnetic character, it is likely that these sediments occupied localised topographic lows, e.g. a river valley, in the pre-Devensian land surface.

ENDPIECE

The pilot data discussed here suggest that the Cley Eye till is Devensian in age, as suspected by Brian Funnell. This interpretation extends the presence of Devensian till on the north Norfolk coast eastward of Morston (mouth of the River Stiffkey), the locality that Straw (1960) regarded as the 'final appearance' of the 'Hunstanton' Till. This interpretation is supported by recent (between 1997 and 2000) 1:10 000 scale re-mapping between Wells-next-the-Sea and Weybourne (Fig. 3) by the British Geological Survey (BGS). This mapping has revised the distribution of the Hunstanton Till (to be renamed the Holkham Till Member of the Holderness Formation (Cromer 1:50 000 geological sheet, British Geological Survey, in press). The 'eye' deposits (Blakeney Eye to Gramborough Hill) are mapped by the BGS as the Ringstead Sand and Gravel Member of the Holderness Formation. These are interpreted as a series of low glaciofluvial ridges, mounds and degraded meltwater channels that mark the probable southern limit of Late Devensian glaciation in north Norfolk (Fig. 3). The 'eye' deposits are clear evidence that Devensian meltwater drainage (see also Brand *et al.*, 2002) occupied the area. The Devensian 'eye' deposits do not, however, demonstrate that the coast parallel trough (Chroston *et al.* 1999) is a Devensian meltwater channel because this feature also appears to contain much older sediments with 'Anglian magnetic character'.

Fig. 3 (facing page). Simplified geological map of the area between Wells-next-the-Sea and Salthouse, north Norfolk, based on BGS 1:10 000 scale mapping. Note that the glacial 'eyes' in the coastal marshes between Blakeney and Salthouse are mapped as the Ringstead Sand and Gravel Member of the Holderness Formation. The Cley Eye till is marked as a beach outcrop.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NORTH SEA
Low Tide Line
Blakeney Point
Beach outcrop of Holkham Till Member
Blakeney Eye
Cley Eye
Cley Marshes
Little Eye
Gramborough Hill
Salthouse
Marshes
Fresh Marshes
WELLS-NEXT-THE-SEA
Warham Salt Marshes
Red Lion Stiffkey outcrop
Stiffkey Marshes
Morston outcrop
Morston
Blakeney
Cley next the Sea
Salthouse
Holt
Binham
DRIFT
Alluvium, Tidal Flat and Tidal Creek deposits
Peat
Head
Ringstead Sand and Gravel Member of the Holderness Formation
Holkham Till Member of the Holderness Formation
Chelky Till and sends and gravels undifferentiated
SOLID
Chalk (bedrock)
Probable maximum extent of the late Devension ice margin (lying to the north)
0
1 km

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BACK ISSUES OF THE BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK AND 50th JUBILEE VOLUME

The Geological Society of Norfolk (GSN) has recovered back issues of the Bulletin that have until recently languished in Norwich castle. These back issues are available for purchase as outlined below. The Bulletin may not be easily available at some institutions - except through Inter-Library Loan – so individuals might consider a recommendation for purchase by institution libraries.

At present we can supply all issues except volumes 19, 32 and 42. Volumes 23, 27 and 28 are in short supply (less than 10 remaining). Volumes 1-10 and 11-18 are only available as reprint volumes 38A and 39A.

There are plenty of copies of the now famous 'East Anglian Geology' issue, volume 34.

Back issues of the Bulletin are available at £3-50 per issue to GSN members and £10-00 per issue to non-members. For purchase of two or more issues it is cheaper for non-members to join the society (£10-00 per year) and buy at member price.

In addition, the society has recently published a special Jubilee volume (edited by Roger Dixon) to commemorate its 50th anniversary. This volume is dedicated to Prof. Brian Funnell and contains a number of articles about Prof. Funnell, his research and the early days of the Society. The Jubilee Volume is free to GSN members. The remainder will be sold at cost (£8-50). Sales will be made on a first come first served basis.

If you would like to place an order please discuss your requirements with Julian Andrews at UEA, preferably on the following e-mail address: j.andrews@uea.ac.uk

Or by post to: Dr Julian Andrews, School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ.

ON THE OCCURRENCE OF ECHINOID SPINES REFERABLE TO THE FAMILY ECHINOTHURIIDAE THOMSON, 1872 FROM THE NORWICH CHALK

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The two Cretaceous echinoid spines discussed in this note were recovered from an old Chalk pit, recorded by the author as the Groundsman's Pit, Earlham Park, Norwich [TG 191 081], adjacent to the University of East Anglia. The outcrop is located behind the groundsman's tool shed. The chalk in this the pit belongs to the upper Upper Campanian, zone of *Belemnitella mucronata*, Pre-Weybourne 3 Chalk as defined by Wood (1998) (= zone of *B. mucronata* sensu Christensen (1995)).

The specimens were recovered by wet-sieving batches of a 5kg sample through a 1 mm sieve. Recovered specimens were allowed to dry and then picked out under low magnification using a binocular microscope.

The spine fragments discussed here (the better preserved of which is shown in Fig. 1) were identified as echinoderm material by virtue of their stereom structure. Their hoof-shaped morphology is unique amongst echinoid material previously recovered from Norwich Chalk samples.

The spines were identified as belonging to a member of the Echinothuriidae Thomson , 1872 by reference to Smith and Wright (1990), who state that hoofed primary spines are diagnostic of the family. These authors remark that *Echinothuria floris* Woodward (recorded from the British Santonian) is known to have hoofed spines. However, they also note that hoofed spines described from the Chalk of continental Europe are insufficient for making generic or specific identification. This is the first record of these extremely rare fossils in the Chalk of Norfolk.

Modern day representatives of the family are exclusively deep-water forms. This makes their discovery in association with a diverse and abundant lunulitid bryozoan fauna - a group known to prefer shallower waters - remarkable. It may be that competition

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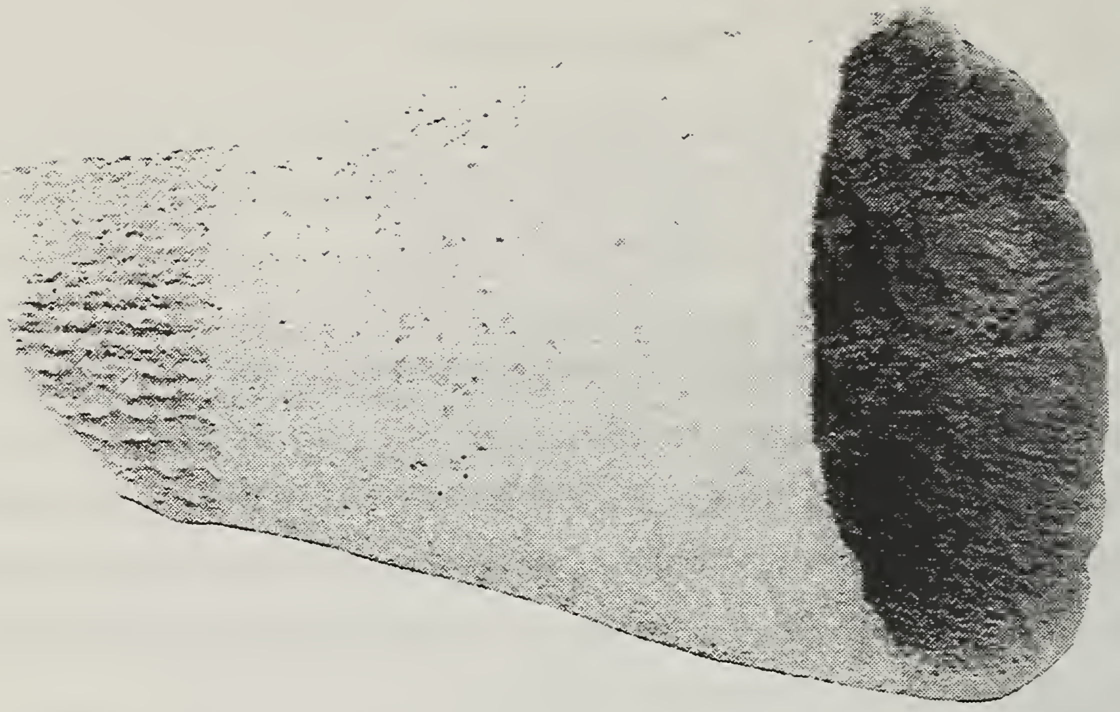

Fig. 1. Broken tip of primary spine of specimen UEA(?)26/1. Spine tip is 2.5 mm long.

from other benthic organisms has forced these echinoids into their modern day deep-water niche sometime since the end of the Cretaceous.

Material examined

UEA(?)26/1. Well preserved tip of primary spine

UEA(?)26/2. Poorly preserved tip of primary spine

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REPORT OF SOCIETY FIELD MEETINGS IN 2001

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INTRODUCTION

This account describes only those field meetings organised in conjunction with the Suffolk Naturalist Society and led jointly by Bob Markham and the author. The first two field meetings of the season, 'Kings Lynn springs and pingoes' and 'Box-stone Bonanza' were cancelled because of the foot-and-mouth epidemic.

WEYBOURNE CLIFF

Saturday 21st July

Five participants attended on this dry but breezy and mostly sunny day to the North Norfolk coast, on a trip aimed to complement that to West Runton last year. The party walked eastwards along the cliff-top and dropped down to beach-level after about 2km.

The Chalk (Campanian), the base of the local succession, forms the bottom part of the cliff. Its surface is quite weathered in places, with solution hollows and pits, some of which are Crag filled. This was best seen nearer the car park. As the tide receded later in the afternoon, the Chalk wave-cut platform gradually became exposed, enabling a better search for fossils, which included sponges and belemnites.

The unconformably overlying Stone Bed and Weybourne Crag were very well exposed and form discontinuous lenses. The basal bed comprises rounded, well cemented and iron-stained flint pebbles, followed by shelly sands passing up into gravels and then loamy sands and laminated sands and silts. The shells have a weathered appearance and may be partially reworked; they indicate a pre-Pastonian/Pastonian cold water fauna with *Macoma*, *Cardium* and *Nucella* particularly common (for discussion see Allen & Keen 2000).

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The Crag is overlain by the Cromer Tills (=Contorted Drift). The area demonstrates complicated structural and enigmatic relationships, and has stimulated much recent research. Readers are referred to Fish *et al*. (2000a & 2000b) for details.

On return to the car park, the view of Muckleburgh Hill to the west was observed. The traditional interpretation of the hill is that it is a 130,000 year-old kame. However, subsequent post-depositional erosion may have left this hill as a residual outlier of the Kelling Sandur.

THE SUDBURY AREA

Saturday 4th August

Nine people attended this meeting on a bright and sunny day (apart from one lunch-time shower) to examine the stratigraphy of the Sudbury area. At one time there were many working Chalk and clay pits in the area and, even 30 years ago, outcrops were quite good. This is not the case now today. We visited five former pits – Lower Alexandra Brickworks (now a housing estate), Railway Chalk Pit (housing), Great Cornard Brickworks (overgrown), Brundon Lane (much infilled) and the Victoria Pit (housing). However, sufficient was exposed to be able to gain an excellent overview of the succession in this interesting and often neglected area.

The *Marsupites* zone Chalk forms the bottom of the sequence. It is soft and marly here, with relatively few flints. It is overlain unconformably by the Lower London Tertiaries – the area lies just south of the NW limit of these beds, and just on the limit of London Clay. The Bull Head Beds, with the 'devils dung' flint pebbles and glauconitic clayey greensand, mark the base of the Tertiaries, followed by up to 4m of brownish Thanet Beds sands. These are overlapped by 3m of impersistent Reading Beds – brown mottled clays interdigitated with subordinate sands which exhibit cross-bedding.

The still enigmatic 'Red Crag' (6m max) lies unconformably on Tertiaries or Chalk, forming remnant outliers and marking the western limit of the formation. It comprises ferruginous sands, cross-bedded in part, with ironstone bands, which occasionally contain the casts of shells and therefore indicate that decalcification has taken place. There is a basal pebble bed containing phosphatic nodules, rolled Tertiary clay pebbles, bone and teeth; shells are rarely found, and are rolled, broken and weathered – a list is given by Boswell (1929, p27), suggesting 'Waltonian' age.

The overlying Pleistocene caused much comment. Historically this area once showed "the finest inland sections of Drift in the kingdom" (Boswell 1929), with Chalky Boulder

Clay passing down into bedded silts, often much contorted, and deposits of sands, silts and brickearth. At Brundon Lane 210,000 year-old cross-bedded river terrace gravels are found. These interglacial gravels contain abundant *Gryphaea* and belemnites, and a well documented mammal fauna, which includes elephant, 'elk', bear, horse and deer. Several pieces of bone were found by participants. The site has also yielded Lower Palaeolithic flakes. There was discussion of buried channels and their morphology, the origin and development of river systems, 'pre-diversionary' drainage and the proto-Thames.

PAKEFIELD

Saturday 15th September

Eight members attended this meeting on a sunny September day. After a briefing by Bob Markham, illustrated with Blake's 1884 Geological Survey section (produced by Roger Dixon), the party descended from the caravan park 1km north of Kessingland onto the beach. After several decades of cover by slipped material, exposures of the cliff section have been quite good for the last five years due to renewed coastal erosion along this stretch of coastline.

The group walked northwards, examining first the Anglian Jurassic-rich Chalky Boulder Clay. Several ammonites, belemnites, *Gryphaea*, septaria and fragments of bituminous Kimmeridge Clay (prompting discussion of Norfolk's oil industry) were found in this sticky till.

The underlying Corton Beds were also clearly exposed. These sands, c.8m in thickness, are interpreted as distal proglacial outwash deposits, formed to the south of the Scandinavian ice sheets about 440,000 yrs BP. They are moderately well-sorted, fine to medium-grained pale yellow sands with occasional pebbles; they exhibit well-developed medium and small-scale cross bedding, with climbing ripples and ripple drift of particular interest. Current directions indicate flow generally to the south, away from the ice sheet.

The lowest beds seen were those traditionally attributed to the Cromer Forest Bed – a sequence of compressed muds and laminated silty clays, some of which contain much woody material and from which a significant mammal fauna is recorded, including lion, mammoth, deer, hippopotamus and bison (Stuart & Lister 2000). Part of the sequence, a well-developed Rootlet Bed, is interpreted as an alluvial over-bank floodplain deposit and pollen analyses suggest deposition in a warm, temperate phase in the early Middle Pleistocene.

Lunch was taken at Crazy Mary's Hole (Lighthouse Gap), before proceeding 200 metres further north to examine some curious and unidentifiable vertical burrow systems in the Forest Bed Formation. The party then retraced its steps, further inspecting the section.

EAST MERSEA

Saturday 13th October

Thirteen people attended this meeting in Essex on a beautiful sunny day to visit a classic Quaternary SSSI. While gathered in the car park, John Llewellyn-Jones, Natural History Curator at the West Mersea Museum, exhibited a tooth of *Elephas antiquus*, which had been found at this site and is to be displayed in the museum. Excellent descriptions and discussion of the section can be found in Bridgland *et al.* (1995).

Commencing at Cudmore Grove, at the eastern end of the section, we examined first the flinty Mersea Island Gravel, interpreted as a cold pre-Ipswichian proto-Thames-Medway deposit. Of particular interest was the small and medium scale cross bedding seen in some of the more sandy beds, indicating current directions generally towards the south-west, and the convolutions seen in a silty layer, which may have resulted from post-depositional dewatering.

Underlying the gravels are the temperate Hoxnian Cudmore Grove channel deposits. The channel is cut deeply into the London Clay, extending some 11m below OD, and is infilled with a sequence of silts and clays. The lower channel beds contain abundant *Hydrobia* and *Cerastoderma*, indicating brackish, estuarine or intertidal conditions. These were clearly exposed on the upper foreshore, revealed as the tide receded. The overlying sediments contain freshwater shells and an impressive assemblage of vertebrates, including voles, shrews, beaver, monkey and tortoise (Bridgland *et al*., 1988). Organic silty clays, containing wood fragments, make up the upper part of the sequence.

The London Clay is exposed in the central part of the cliff section and over much of the foreshore. It is a sticky blue-grey clay, weathering to a rusty brown. No fossils were found, but several pieces of pyritised wood were found on the shore.

The western part of the section is marked by a second channel cut into the London Clay and containing the Restaurant Gravels, proto-Blackwater fluvial deposits of temperate Ipswichian age. The gravels contain higher percentages of quartz and quartzite than the Cudmore Grove Gravels, and freshwater molluscs and mammals including hippopotamus, rhinoceros and elephant. 'Brickearth' sand and silt overlie the gravels, but the large amount of talus and overgrowth meant outcrop was poor.

Finally, at the saltings adjacent to the Cosway Holiday Home Park, the party inspected some recent salt-marsh deposits with root beds. This prompted discussion of the dating of recent sediments by animal and plant introductions into Britain.

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The Geological Society of Norfolk exists to promote the study and understanding of geology in East Anglia, and holds meetings throughout the year. For further details consult our Web Site (http://www.uea.ac.uk/env/gsn) or write to The Secretary, Geological Society of Norfolk, 32, Lenthall Close, Norwich, NR7 0UU.

Copies of the Bulletin (including older back copies – see p. 88 this issue) can be obtained from the editor at the address on p.1; it is issued free to members.

The illustration on the front cover is figure 10 from the article by Corbett in this issue of the Bulletin. It shows Anglian ice flow directions and depositional sequences in the Lowestoft Till based on mineral magnetic data.

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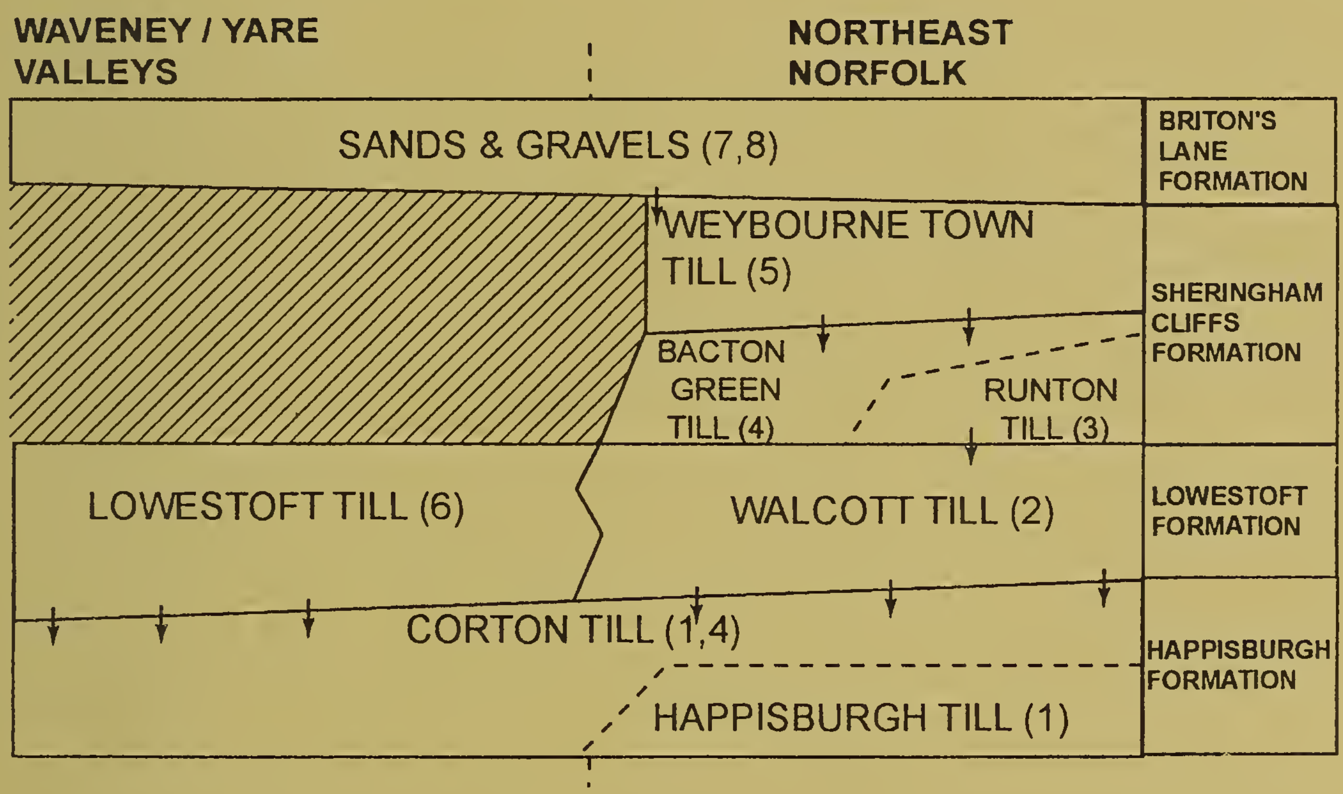

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STRATIGRAPHY

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EDITORIAL

Bulletin No. 53 is devoted to one paper by Jonathan Lee and co-authors from the British Geological Survey and the Department of Geography at Royal Holloway, University of London. The paper describes a revised stratigraphy for the glacial deposits in north eastern East Anglia, a topic that has sparked much recent interest and lively debate in the British Quaternary community. I am very pleased to have such a topical contribution from a group who are valued regular contributors to the activities of the GSN. This paper is an excellent introduction to the current and past stratigraphic nomenclature used for these complex deposits and should aid non-specialists who want to understand the field relations. I am sure the paper will also generate further debate amongst the specialists.

At the time of going to press (July 2004) there are five more papers ready for publication by regular contributors to the Bulletin. Bulletin 54 will therefore soon follow. As always, however, I encourage the continued submission of papers on all aspects of East Anglian geology, both from regular and new contributors.

INSTRUCTIONS TO AUTHORS

Contributors should submit manuscripts as word-processor hard copy. We accept typewritten copy and consider legible handwritten material for short articles only. When papers are accepted for publication we will request an electronic version. We can handle most word-processing formats although MS Word is preferred.

It is important that the style of the paper, in terms of overall format, capitalisation, punctuation etc. conforms as strictly as possible to that used in Vol. 53 of the Bulletin. Titles and first order headings should be capitalised, centred and in bold print. Second order headings should be centred, bold and lower case. Text should be 1½ line spaced. All measurements should be given in metric units.

References should be arranged alphabetically in the following style.

BALSON, P.S. & CAMERON, T.T.J. 1985. Quaternary mapping offshore East Anglia. *Modern Geology*, **9**, 221-239.

STEERS, J.A. 1960. Physiography and evolution: the physiography and evolution of Scolt Head Island. In: Steers, J.D. (ed.) *Scolt Head Island* (2nd ed.), 12-66, Heffer, Cambridge.

BLACK, R.M. 1988. *The Elements of Palaeontology*. 2nd Ed., Cambridge University Press, Cambridge. 404pp.

Illustrations should be drawn with thin dense black ink lines. Thick lines, close stipple or patches of solid black or grey should be avoided as these can spread in printing. Original illustrations should, before reproduction, be not more than **175mm by 255mm**. Full use should be made of the first (horizontal) dimension which corresponds to the width of print on the page, but the second (vertical) dimension is an upper limit only. Half tone photographic plates are acceptable when their use is warranted by the subject matter, provided the originals exhibit good contrast.

The editors welcome original research papers, notes, comments, discussion, and review articles relevant to the geology of **East Anglia** as a whole, and do not restrict consideration to articles covering Norfolk alone. All papers are independently refereed by at least one reviewer.

A NEW STRATIGRAPHY FOR THE GLACIAL DEPOSITS AROUND LOWESTOFT, GREAT YARMOUTH, NORTH WALSHAM AND CROMER, EAST ANGLIA, UK.

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ABSTRACT

A new stratigraphical scheme for the glacial deposits around Lowestoft, Great Yarmouth, North Walsham and Cromer (east of Weybourne and Edgefield) is presented, based on a combined research programme by the British Geological Survey and the Department of Geography, Royal Holloway University of London. This stratigraphical scheme is founded on evidence derived from sedimentological descriptions, geological mapping and analytical lithological techniques including clast lithological analysis, derived pre-Quaternary palynomorphs and heavy mineralogy. The previously accepted 'North Sea Drift'/'Lowestoft Formation' scheme is abandoned in favour of four formations that relate to assemblages of till units and associated outwash lithofacies, the mapping of major discontinuities, and morpho- and tectono-stratigraphical associations. The new scheme consists of the Happisburgh, redefined Lowestoft, Sheringham Cliffs and Briton's Lane formations.

INTRODUCTION

Glacial sediments in northern East Anglia have been the focus of scientific investigation since the Geological Survey originally mapped the region in the late nineteenth century (Reid, 1882; Blake, 1890). Attention has centred primarily on stratigraphical correlation, the sedimentology of the deposits (Harmer, 1909; Boswell, 1914, 1916; Banham, 1968; Ranson, 1968; Lunkka, 1994; Hart & Boulton, 1991a), and using the tills as ancient

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analogues for testing new models of glacial deposition derived from modern glacial environments (Eyles *et al.*, 1989; Hart *et al.*, 1990; Hart & Boulton, 1991b; Hart & Roberts, 1994; Lee, 2001).

Despite the vast quantity of published material, comparatively little quantitative data has been ***published*** with respect to the lithology of the glacial sediments. This is problematic as it negates hypothesis testing. For example, it has been widely accepted that northern East Anglia was glaciated by Scandinavian ice (Cromer Tills / North Sea Drift) during the Middle Pleistocene (Perrin *et al.*, 1979; Bowen *et al.*, 1986; Ehlers & Gibbard, 1991; Bowen, 1999), despite there being no published evidence to demonstrate this (Moorlock *et al.*, 2001).

Clearly an understanding of sediment lithology, together with sedimentological and structural properties is a critical component in constructing a robust and demonstrable lithostratigraphic framework (Salvador, 1994; Rawson *et al.*, 2002), as well as for modelling sediment provenance and patterns of glaciation. For this reason a joint research programme of the British Geological Survey and the Department of Geography at Royal Holloway University of London was instigated to examine the stratigraphy and palaeoenvironments of the glacial deposits of East Anglia. This paper presents a summary of the results of this survey in the areas of Lowestoft, Great Yarmouth, North Walsham and Cromer (Fig. 1). It is envisaged that our new glacial stratigraphy will provide a robust foundation and standard nomenclature for future research within the region, as well as offering the conceptual basis upon which presently accepted explanations for the glacial history of the region can be tested.

The specific aims of this paper are firstly, to present the new glacial stratigraphy for the region; and secondly, to use this data to test some of the major concepts that underlie the glacial history of the region.

HISTORY OF GEOLOGICAL INVESTIGATIONS

Stratigraphy

Previous lithostratigraphical schemes for the glacial deposits of northeast Norfolk and the Waveney Valley are shown in Tables 1 and 2. The first detailed stratigraphic investigation of glacial sediments in the area (Fig. 1) coincided with the original mapping survey of the region by officers of the Geological Survey in the late nineteenth century (Reid, 1882; Blake, 1890). Working around Lowestoft and Great Yarmouth, Blake (1890) identified two tills that corresponded to the ‘Lower’ and ‘Upper Glacials’,

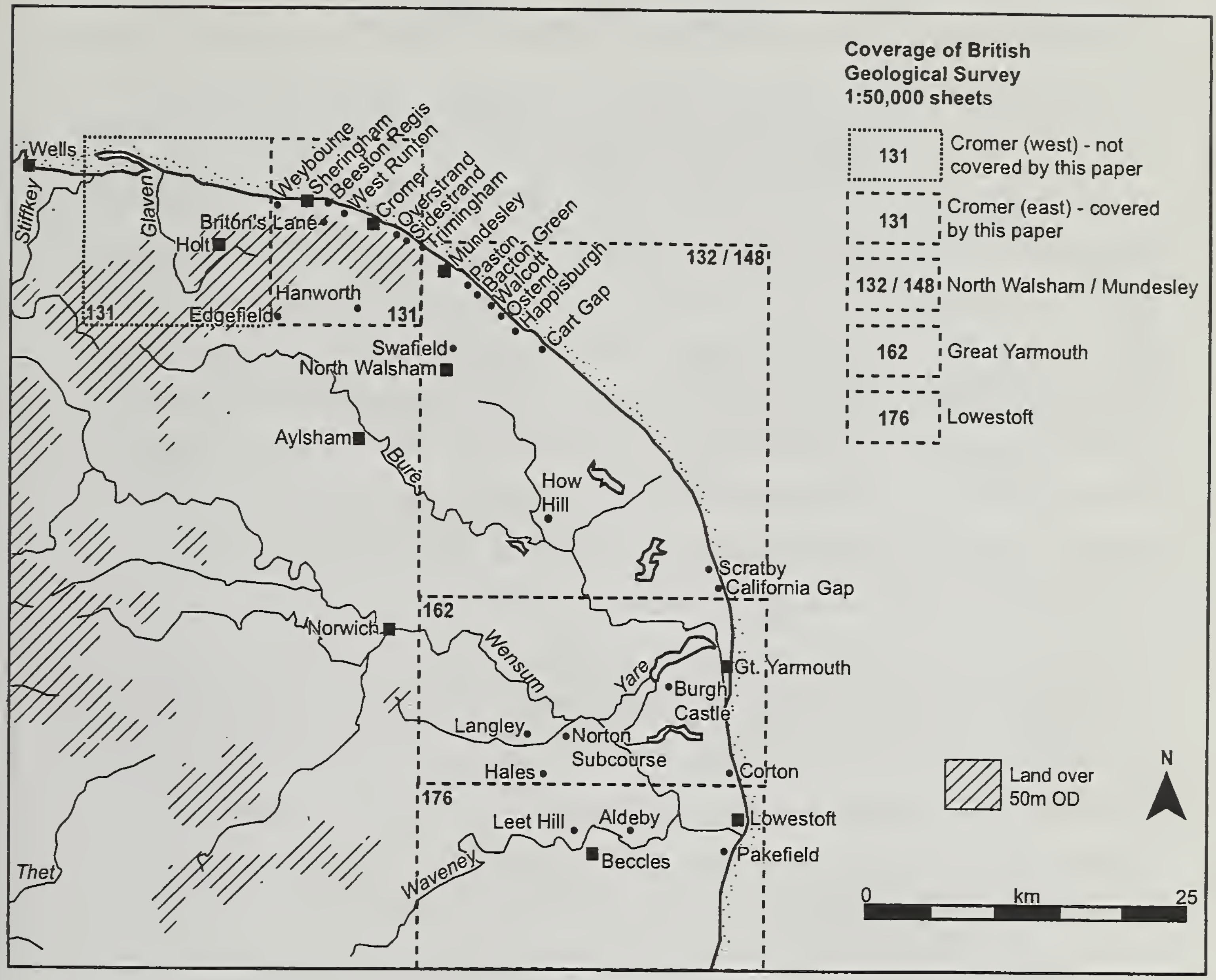

Fig. 1. Location of sites and British Geological Survey 1:50,000 map coverage of the region. Note that this paper only covers the eastern half of Cromer sheet (Sheet 131) sited to the east of the Glaven Valley.

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separated by an intervening 'Middle Glacial' sand unit. In northeast Norfolk, Reid (1882) recognised a tripartite till sequence separated by a series of outwash deposits. He termed the tills the 'First' and 'Second Tills' (Cromer Till association) and the 'Boulder Clay / Stony Loam' and was able to trace them individually between Happisburgh and Mundesley before they passed northward into the 'Contorted Drift' (Trimingham – Weybourne) (Table 1). In this area Reid argued that a stratigraphical succession was impossible to determine due to intense deformation. This melange of deformed

Table 1. Previous lithostratigraphical schemes for the glacial deposits of northeast Norfolk based on Reid (1882), Banham (1968) and Lunkka (1994).

REID (1882)	BANHAM (1968)	LUNKKA (1994)	
	Briton's Lane Sand & Gravels		NORTH SEA DRIFT FORMATION
Boulder Clay	Marly Drift	Marly Drift	LOWESTOFT FORMATION
Clays		Trimingham Sands & Clays	
Sands	Gimingham Sands	Stow Hill Sands	
Boulder Clay / stony loam	Third Cromer Till	Cromer & Mundesley diamictons	
Sands	Mundesley Sands	Upper Mundesley Sands	NORTH SEA DRIFT FORMATION
Second Till	Second Cromer Till	Walcott Diamicton	
Intermediate Beds	Intermediate Beds	Lower Mundesley Sands & Happisburgh Clays	
First Till	First Cromer Till	Happisburgh Diamicton	

Table 2. Previous lithostratigraphical schemes for the glacial deposits of the area around Great Yarmouth and Lowestoft after Banham (1971), Pointon (1978) and Bridge & Hopson (1985).

BANHAM (1971) POINTON (1978)	BRIDGE & HOPSON (1985)	
Plateau Sands and Gravels	Corton Woods Sands & Gravels	
Pleasure Gardens Till	Pleasure Gardens Till	LOWESTOFT FORMATION
Oulton Beds	Oulton Beds	
Lowestoft Till	Lowestoft Till	
Corton Beds	Corton Sands	NORTH SEA DRIFT FORMATION
	Leet Hill Sands and Gravels	
Cromer Till	Norwich Brickearth	

sediment was overlain by a series of highly chalky tills deposited by British ice that were later to become known as the 'Marly Drift' (Banham, 1968; Lunkka, 1994).

Following Reid and Blake, the next major stratigraphical studies undertaken in the region were those of Harmer (1909) and Boswell (1914, 1916). Their work led to the introduction of the now familiar term 'North Sea Drift' which was used to encompass the 'Cromer Till' and 'Contorted Drift' associations of Reid (1882), due to the reported occurrence of erratics and heavy minerals of North Sea and Scandinavian provenance, and their inferred stratigraphical correlation with tills of Scandinavian origin ('Lower Glacial') that underlie British tills ('Upper Glacial') within the County Durham area (Trechmann, 1916).

A notable hiatus in research occurred during the inter-war years. However, following World War II, Baden-Powell (1948, 1950) published two influential papers concerning the stratigraphy of central East Anglia and the Lowestoft area. He confirmed the sequence identified at Corton by Blake (1890) and renamed the 'Lower Glacial' and 'Upper Glacial' as 'Norwich Brickearth' and 'Chalky Boulder Clay' respectively. He also recognised two distinctive facies of 'Chalky Boulder Clay', a Jurassic-rich facies (i.e. Lowestoft-type) and a chalk-rich facies (i.e. Gipping-type), and concluded that they were deposited during separate Anglian and 'Gipping' glaciations.

During the 1960s and 1970s Banham and Ranson undertook a major research programme in northeast East Anglia. They adopted a litho- and tectono-stratigraphical approach and constructed a similar sequence, albeit more elaborate, to that originally defined by Reid (1882) and Blake (1890) (Tables 1 and 2). Tills were renamed as the now familiar First, Second and Third Cromer Tills of the 'North Sea Drift' (Banham, 1968, 1971; Ranson, 1968a) which Banham (1968, 1975) recognised could be traced laterally into the Contorted Drift. Banham (1971) and Pointon (1978) also investigated coastal sections at Corton and replaced the term 'Chalky Boulder Clay' (Corton-type) coined by Baden Powell (1948), with 'Lowestoft Till'.

Banham's stratigraphical classification was subsequently adopted following a stratigraphical review of Quaternary deposits in the British Isles by the Geological Society (Mitchell *et al.*, 1973). Two separate glaciations were assumed to have occurred during separate stadials of the Anglian Glaciation. The first of these, the Gunton Stadial, related to an initial advance of Scandinavian ice into the region that deposited the 'Cromer Tills'/'North Sea Drift Formation'; during the second Lowestoft Stadial glaciation, the 'Lowestoft Till' was laid-down by British ice. Within the intervening Corton Interstadial, the 'Corton Beds' ('Middle Glacial' of Blake, 1890) were deposited. Subsequent work has challenged the validity of this climostratigraphical interpretation of the Anglian Glaciation, due to the presence at Weybourne of intercalated North Sea Drift and Lowestoft Till (Banham *et al.*, 1975), and the reinterpretation of the Corton Beds as outwash derived from the North Sea Drift ice sheet (Bridge & Hopson, 1985; Rose, 1989).

The first detailed quantitative investigation of tills within the region was undertaken by Perrin *et al.* (1973, 1979). They used the spatial distribution of till matrix properties ($CaCO_3$, matrix texture, heavy mineralogy) to determine: (1) that all chalky tills of eastern England, namely the 'Chalky Boulder Clay' (Jurassic- and chalk-rich types) and 'Marly Drift' of north Norfolk, formed a single till sheet that was deposited by ice fanning-out over different bedrock lithologies from the Wash and Fenland Basins – this till sheet was subsequently called the Lowestoft Till after Banham (1971) and Mitchell *et al.* (1973); (2) that tills of 'North Sea Drift' and 'Lowestoft' affinities possessed different lithological properties. The original model of Perrin *et al.* has been elaborated and superseded by subsequent work (Rose, 1992; Fish & Whiteman, 2001).

The 1980s marked a distinctive point of divergence in approaches to stratigraphy. The lithostratigraphical and mapping approach was adopted by the British Geological Survey who had just begun remapping the Waveney Valley. Using the sequence described at Corton by Blake (1890) and Banham (1971) as a regional stratotype, they were able to correlate stratigraphical units back to the Corton type-area via mapping, boreholes, and subsurface geometry (Bridge & Hopson, 1985; Hopson & Bridge, 1987; Arthurton *et al.*, 1994). In contrast, the work of Hart and Boulton (Hart, 1987, 1990, 1992; Hart & Boulton, 1991a) and later Lunkka (Lunkka, 1988, 1991, 1994) in northeast Norfolk followed a more process-based stratigraphical rationale that, particularly in the case of the Hart and Boulton, was strongly influenced by research in modern glacial environments. The stratigraphical scheme proposed by Lunkka (1994), although similar to that of Banham (1968) and Ranson (1968a), was considerably expanded with a total of five diamicton units – Happisburgh Diamicton (=First Cromer Till), Walcott Diamicton (=Second Cromer Till), Cromer and Mundesley Diamictons (=Third Cromer Till), and Marly Drift (=Lowestoft Till) (Table 1).

A modified version of Lunkka's stratigraphical scheme was subsequently adopted by the Geological Society of London for northeast East Anglia in their recent reclassification of the Quaternary deposits of the British Isles (Bowen, 1999). Within this scheme, two major lithofacies associations are present: (1) the North Sea Drift Formation of Scandinavian provenance; (2) the Lowestoft Formation deposited by British Ice. However, this scheme has several problems – most notably the complexity and inaccessibility of the stratigraphical nomenclature, and the failure to resolve the fundamental problem of synchronising the successions of northeast Norfolk and the Waveney Valley.

Chronology of glaciations

The Geological Society correlation of Quaternary deposits in Britain states that the region was glaciated just once during the Middle Pleistocene – an event that corresponds to the Anglian Glaciation (c. 480-430ka) (Mitchell *et al.*, 1973; Bowen, 1999). This view, has been generally accepted by most workers (e.g. Bowen *et al.*, 1986; Hart & Boulton, 1991a; Lunkka, 1994), but not by all. Firstly, it is not clear that the chalky tills of East Anglia correspond to one extensive till sheet (Lowestoft Till) deposited during the Anglian (Bristow & Cox, 1973; Perrin *et al.*, 1979; Rose, 1992); it could be that there are several lithologically similar till sheets deposited during different Middle Pleistocene glaciations (Baden-Powell, 1948; West & Donner, 1956; Straw, 1979, 1983). Most recently, Hamblin *et al.* (2000, 2001), Lee (2003) and Clark *et al.* (2004) have argued that only the Lowestoft Till and the Second Cromer Till / Walcott Diamicton of the 'North Sea Drift' are Anglian, and that the First Cromer Till / Happisburgh Diamicton and the Third Cromer Till / Cromer / Mundesley Diamictons may relate to older and younger Middle Pleistocene glaciations respectively. This concept has been challenged by some (Banham *et al.*, 2001; Preece, 2001; Whiteman, 2002), and is the focus of present research within the region. A detailed review of this chronological debate is beyond the scope of this paper as its primary focus is stratigraphic; readers are directed to the above publications and to Lee *et al.* (2004).

RESEARCH STRATEGY AND METHODOLOGY

Stratigraphical approach

The primary aim of this research was to devise a robust and accessible stratigraphical scheme that conforms to modern stratigraphic protocols (Salvador, 1994; Rawson *et al.*, 2002), and one that was not biased by pre-conceived or out-dated stratigraphical and palaeoenvironmental models. With this in mind, the following hierarchical stratigraphical approach was applied:

1. Field description and lithological analyses of deposits at individual sites.
2. Identification and definition of 'lithofacies' at stratotype localities / areas based on lithological, mineralogical, sedimentological and textural properties, geometry, geomorphological context and relative stratigraphical position. This provided a practical and conceptual basis for:
    a. Correlation of lithofacies between sites;

   b. Geological mapping based on recognition of type-lithofacies – especially diamictons and some of the more identifiable sands and gravels;

3. Construction of 'members' within the stratigraphical scheme based upon the spatial correlation of lithofacies. Where possible this has utilised and adapted pre-existing stratigraphical terms (e.g.. Corton Sands = Corton Sand Member).
4. Placement of 'members' within 'formations' based upon lithofacies associations and mappable disconformities. An important characteristic of the 'formation' is that it is the fundamental mapping-based unit (Salvador, 1994).

Analytical Methodologies

A range of analytical techniques was used to generate the data that underpins the stratigraphy. Lithofacies at individual sites were described on the basis of texture, lithology, colour (Munsell Colour value), structure (sedimentary and tectonic), geometry and the nature of lower and upper contacts (Tucker, 1996). Orientation measurements such as clast fabric (a-axis measurements), shear plane, fold and palaeocurrent determinations were also collected to provide information concerning palaeo stress-fields and palaeoflow. Lithological analyses were undertaken on bulk samples to quantify their lithological properties, aid stratigraphical correlation and provenance determination. Particular emphases were placed on particle size distribution, calcium carbonate content, derived palynomorphs, clast lithological analysis of diamictons and heavy mineral analyses — sampling, processing and counting procedures followed standard recommendations (Gale & Hoare, 1991). Diamicton units were also investigated using micromorphological techniques to gain further understanding of their genesis and post-depositional history. Other analytical detail is given in the relevant figure captions.

LOCATION AND GEOMORPHOLOGY OF THE RESEARCH AREA

The geographical area covered by this paper includes the stretch of coastline and adjacent hinterland areas between Weybourne in northern Norfolk, and Pakefield in northern Suffolk. It corresponds to the area in East Anglia recently mapped by the British Geological Survey as part of the Eastern England Mapping Programme and includes the following 1:50,000 sheets with accompanying memoirs and sheet explanations: Lowestoft (Sheet 176; Moorlock *et al.*, 2000b), Great Yarmouth (Sheet 162; Arthurton *et al.*, 1994), North Walsham and Mundesley (Sheet 148 / 132; Moorlock *et al.*, 2002a) and Cromer (east) (Sheet 131; Moorlock *et al.*, 2002b). Coverage of the Cromer sheet (Sheet

131) in this paper is restricted to the eastern half, east of a line that links Weybourne and Edgefield (Fig. 1). The geology of the area immediately to the west that includes Holt, the Glaven Valley and adjoining 1:50,000 Wells sheet, is not discussed in this paper. Geological investigations in this area are currently being undertaken by the authors and results will be presented at a later date.

The southern sector of the study area encompasses the area around Beccles, Great Yarmouth and Lowestoft and the lower reaches of the River Yare and Waveney. Coastal exposures are present at Pakefield, Corton, California Gap and Scratby although their quality and accessibility are variable due to coastal defences and local cliff instability. Inland within the valley flanks, several quarries (many now disused) such as Leet Hill and Norton Subcourse provide good access to glacial deposits (Rose *et al.*, 1999a; Lee, 2003). The stratigraphy in this area is further supported by extensive borehole evidence (Hopson & Bridge, 1987; Arthurton *et al.*, 1994; Rose *et al.*, 2002). Northwards between Scratby and Happisburgh, and inland as far west as Wroxham and North Walsham, the topography consists of a relatively low-lying till plateau incised by the Rivers Bure and Thurne. Exposures in this area are rare, limited to trial pits and occasional now disused brick- and sand- pits; even coastal exposures are poor because the cliffs are replaced by extensive dune fields. The valley floors consist of small rivers, marshes and dykes, collectively the Norfolk Broads, mapped as Holocene alluvium of the Breydon Formation (Arthurton *et al.*, 1994). Further northwards into northeast Norfolk, the topography becomes more undulating rising gently to 100m OD in the vicinity of the Cromer Ridge between Cromer and Sheringham. Coastal sections between Happisburgh and Weybourne are generally good although beach defences and cliff falls, particularly in the south of the region around Mundesley and Trimingham, can restrict access to good sections. Additionally, several working sand and gravel quarries, and numerous partially back-filled, disused sand and gravel and brick pits exist.

A NEW LITHOSTRATIGRAPHY

The new glacial lithostratigraphy for the area is shown in Table 3 and their lateral equivalence in Figure 2, which also shows the simplified relationship between the previous and the new lithostratigraphical schemes. Previously applied stratigraphical terms for each of the newly-defined members are shown in summary tables for each of the formations (Tables 4, 9, 11, 13). Essentially, all of the major till and outwash units

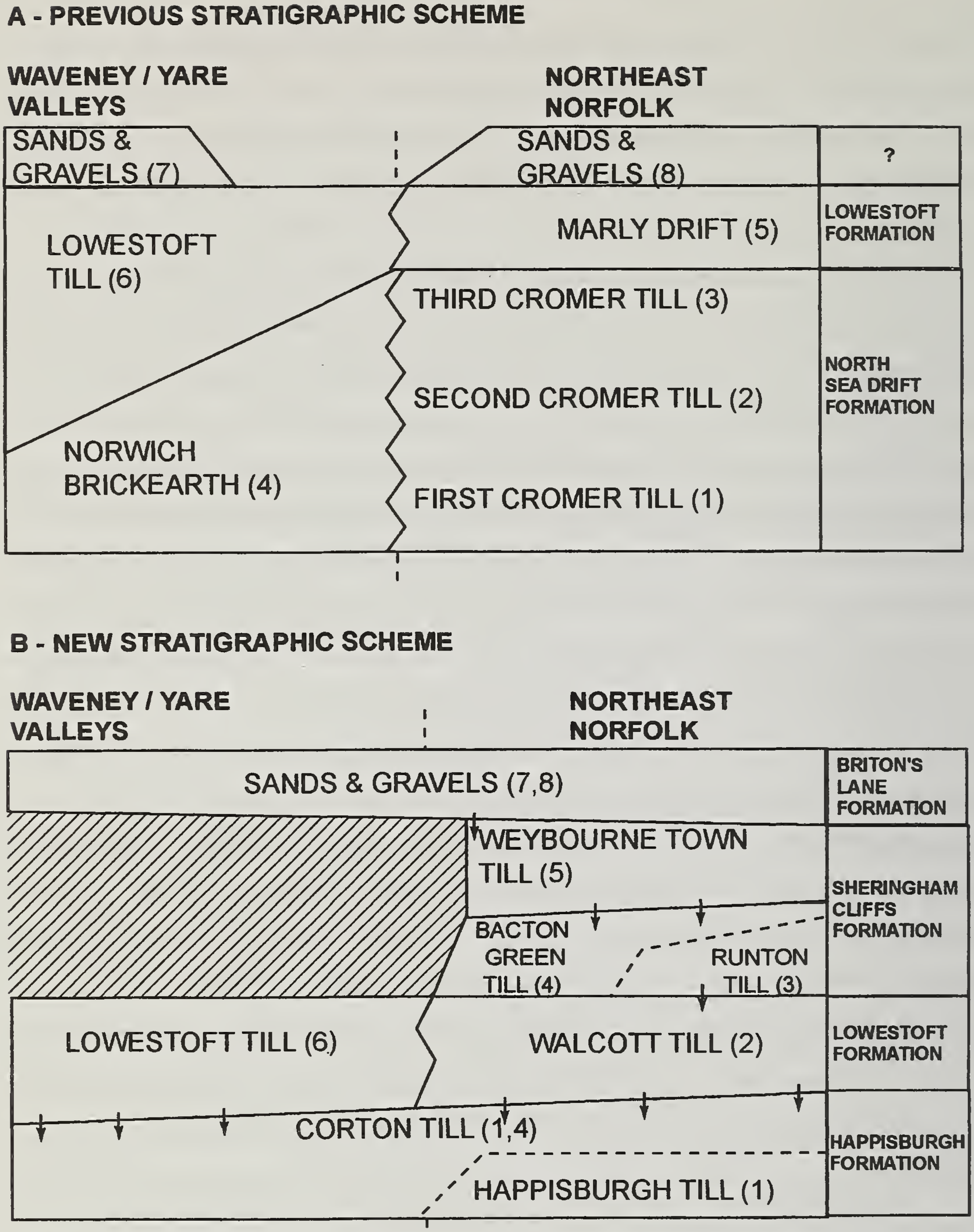

Fig. 2. Glacial stratigraphy of the Lowestoft, Great Yarmouth, North Walsham and Cromer districts. (A) Previous stratigraphical scheme (based on Banham, 1968, 1971) showing relationships between major till and sand and gravel lithofacies of the North Sea Drift and Lowestoft formations in the Waveney Valley and northeast Norfolk. (B) New stratigraphical scheme showing redefined major till and sand and gravel members and formations. Note that each major lithostratigraphical unit within 'A' is assigned a number which corresponds to newly named members within 'B'. Arrows indicate major discontinuities / erosion inferred from mapping.

Table 3. Early-Middle and Middle Pleistocene lithostratigraphy of glacial sediments in the areas of Lowestoft, Great Yarmouth, North Walsham and Cromer. Stratotype area and general lithofacies description of each lithostratigraphical unit is also shown.

LITHOSTRATIGRAPHY **Formation / Member**	**STRATOTYPE AREA**		**LITHOFACIES**
BRITON'S LANE FORMATION			
Briton's Lane Sand & Gravel Member	TG 168415	Briton's Lane, Beeston Regis	Ice-marginal fan complex
Corton Woods Sand & Gravel Member ??	TM 546987	Corton Woods, Corton	Proximal glaciofluvial outwash
Beacon Hill Sand & Gravel Member	TG 284384	Gimingham Quarry, Trimingham	Proximal glaciofluvial outwash
Stow Hill Sand & Gravel Member	TG 328353	Paston Cliffs	Proximal glaciofluvial outwash
SHERINGHAM CLIFFS FORMATION			
Runton Cliffs Sand & Gravel Member	TG 180432	Beeston Cliffs, West Runton	Proximal outwash
Weybourne Town Till Member	TG 114431	Weybourne Town Pit, Weybourne	Subglacial till assemblage – British ice advance from N / NW
Trimingham Sand Member	TG 266397	Trimingham	Local deltaic
Trimingham Clay Member	TG 266397	Trimingham	Low energy glaciolacustrine
Bacton Green Till Member	TG 334347	Bacton Green, Bacton	Subaqueous flow till – grades up from Runton Till Member
Runton Till Member	TG 180432	Beeston Cliffs, West Runton	Subglacial till – British ice advance from NW
Ivy Farm Laminated Silt Member	TG 268397	Sidestrand	Low energy glaciolacustrine
Mundesley Sand Member	TG 325356	Mundesley	Deltaic
LOWESTOFT FORMATION			
Aldeby Sand & Gravel Member	TM 384926	Aldeby	Proximal glaciofluvial outwash
Pleasure Gardens Till Member	TM 546987	Corton Woods, Corton	Flow till – subaqueous?
Oulton Clay Member	TM 546987	Corton Woods, Corton	Low energy glaciolacustrine
Walcott Till Member	TG 391304	Ostend	Subglacial till assemblage – British ice advance from NW
Lowestoft Till Member	TM 546987	Corton Woods, Corton	Subglacial till assemblage – British ice advance from W
HAPPISBURGH FORMATION			
California Till Member	TG 518149	California Gap	Subaqueous flow till
Corton Sand Member	TM 543979	Corton	Distal glaciofluvial outwash; locally tidal
Leet Hill Sand & Gravel Member	TM 384926	Leet Hill	Proximal glaciofluvial outwash
Corton Till Member	TM 543979	Corton	Subglacial till; subaqueous flow till and grounding-line fan
Happisburgh Sand Member	TG 388306	Happisburgh	Deltaic
Ostend Clay Member	TG 388306	Happisburgh	Low energy glaciolacustrine
Happisburgh Till Member	TG 389305	Happisburgh	Subglacial till assemblage – British ice advance from NW

identified in the previous lithostratigraphical schemes have been recognised in the new scheme; however, the major developments of the new scheme are:

1. The 'Cromer Till' and 'North Sea Drift' terminology has been abandoned in favour of a formal stratigraphical nomenclature that contains geographic and litho-genetic qualifiers.
2. Three newly-defined Formations – the Happisburgh, Sheringham Cliffs and Briton's Lane formations are presented together with a re-defined Lowestoft Formation.
3. The 'Walcott Till Member' (formerly Second Cromer Till / Walcott Diamicton) is laterally equivalent to the Lowestoft Till Member.
4. The stratigraphies of the Waveney Valley area (Great Yarmouth and Lowestoft districts) can now be linked directly to those of northeast Norfolk (North Walsham and Cromer districts).

A geological map (Fig. 3) and coastal cross-section (Fig. 4) show the spatial distribution of the Formations, and a series of correlated composite stratigraphical logs (Fig. 5) outline the stratigraphy of key sites, and the spatial distribution of the major lithostratigraphical sub-divisions presented therein. Some of the details of the data, observations and discussion presented in the following sections relate to work that is not yet published; however, it is hoped that papers providing more detail on particular sites and issues will be published in due course.

Happisburgh Formation

The Happisburgh Formation (Table 4) consists of tills and outwash deposits that were previously assigned to the First Cromer Till (Banham, 1968; Ranson, 1968), Happisburgh Diamicton (Lunkka, 1994) or Corton Diamicton (Lee, 2001) and represent sedimentation associated with the oscillating margins of the British Ice Sheet. Cliff sections (TG 3830) to the south of Happisburgh village have been designated the stratotype area for the Happisburgh Formation since they reveal a near complete sequence that enables the stratigraphies of northeast Norfolk and northern Suffolk to be correlated (Fig. 5). Of critical significance is the delineation of the First Cromer Till / Happisburgh Diamicton / Corton Diamicton into two lithologically similar units, the Happisburgh and Corton Till members, that can be separated on the basis of structure and stratigraphical position. Happisburgh Formation sediments crop out widely at the surface throughout the Lowestoft, Great Yarmouth and North Walsham districts (Fig. 3), and have been traced extensively through coastal sections and boreholes as far north as Trimingham (Figs 4 & 5). They commonly overlie, and are in places sedimentologically related to, pre-glacial fluvial and marine deposits of the Bytham Formation and Wroxham Crag Formation respectively (Rose *et al.*, 1999a, 2001; Lee, 2003; Lee *et al.*, 2004).

Happisburgh Till Member

The Happisburgh Till Member is the basal lithofacies of the Happisburgh Formation and crops out at the base of coastal sections between Happisburgh (TG 388304) and Ostend (TG 368322), and further north between Trimingham (TG 288387) and Cromer (TG 230417). It equates to the First Cromer Till of Banham (1968) and Ranson (1968a) or the Happisburgh Diamicton of Lunkka (1994). The unit consists of a 2-7m thick yellowish grey (2.5Y 4/1) to grey (5Y 4/1) matrix-supported diamicton, which has a sandy clay matrix texture (Fig. 6), and is generally massive except for occasional contorted inclusions of chalk and sand. The clast content of the diamicton is typically less than 1% with lithologies largely derived from the reworking of pre-existing Pleistocene deposits (brown, white and chatter-marked flint; quartzose clasts; 65.0-68.1%) and chalk bedrock (15.7-22.8%) (Table 5) (Lee *et al.*, 2002). The lower contact of the unit with underlying pre-glacial Crag sediments is a sharp but irregular, sub-horizontal décollement plane formed during the subglacial accretion of the till as a deforming bed (Hart, 1987; Hart & Boulton, 1991a; Lunkka, 1994; Lee, 2001, 2003). The upper surface of the till is undulating, comprising a series of ridges and troughs that have been interpreted as a range of subglacial and ice-marginal landforms (Hart, 1987; Lunkka, 1988, 1994; Lee, 2003).

Clasts and derived palynomorphs from the till at Happisburgh and Trimingham demonstrate that the ice is of British provenance (Lee *et al.*, 2002). Diagnostic British indicators include Magnesian Limestone clasts from northeastern England, a *Gryphaea arcuata* Lamarck shell from the Lias of Yorkshire, Carboniferous Limestone and coal, plus a Carboniferous palynomorph association characteristic of the Westphalian of central Scotland or northern England (Lee *et al.*, 2002). The far-travelled erratic content strongly suggests of a source in Central Scotland with clasts of low- to medium-grade Dalradian meta-sediments, basaltic and acid porphyry and Old Red Sandstone. No diagnostic Scandinavian lithologies such as rhomb porphyry, larvikite and high-grade

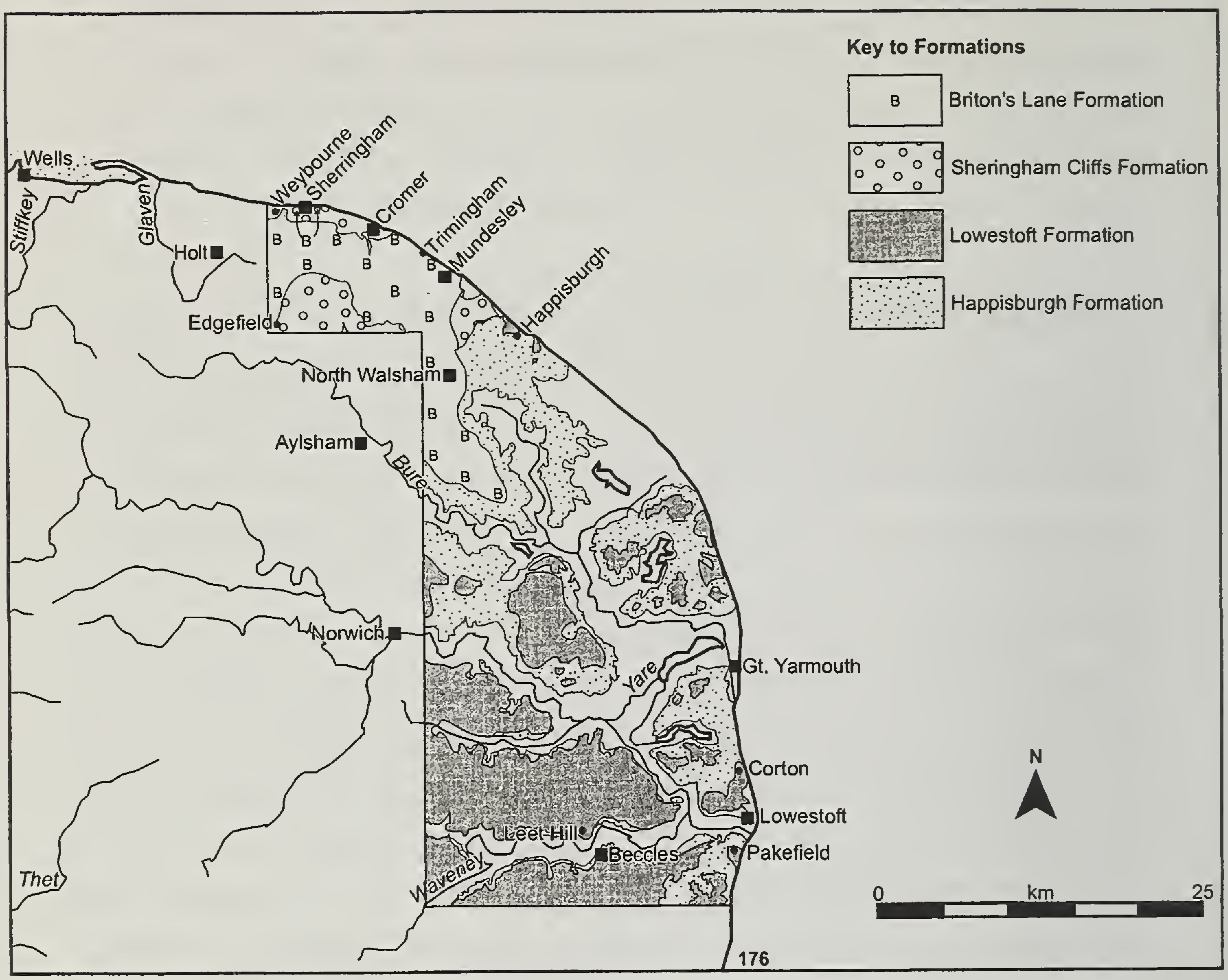

Fig. 3. Geological map of the study area adapted from 1:50,000 sheets Lowestoft (176), Great Yarmouth (162), North Walsham (148), Mundesley (132) and Cromer (131) showing the distribution of the Happisburgh, Lowestoft, Sheringham Cliffs and Briton's Lane formations.

Fig. 4. (facing page) Cross section of coastal sections between Pakefield and Corton in the Waveney Valley, and Cart Gap and Weybourne in north Norfolk. Shown are the major structural elements, and the distribution of the Happisburgh, Lowestoft, Sheringham Cliffs and Briton's Lane formations.

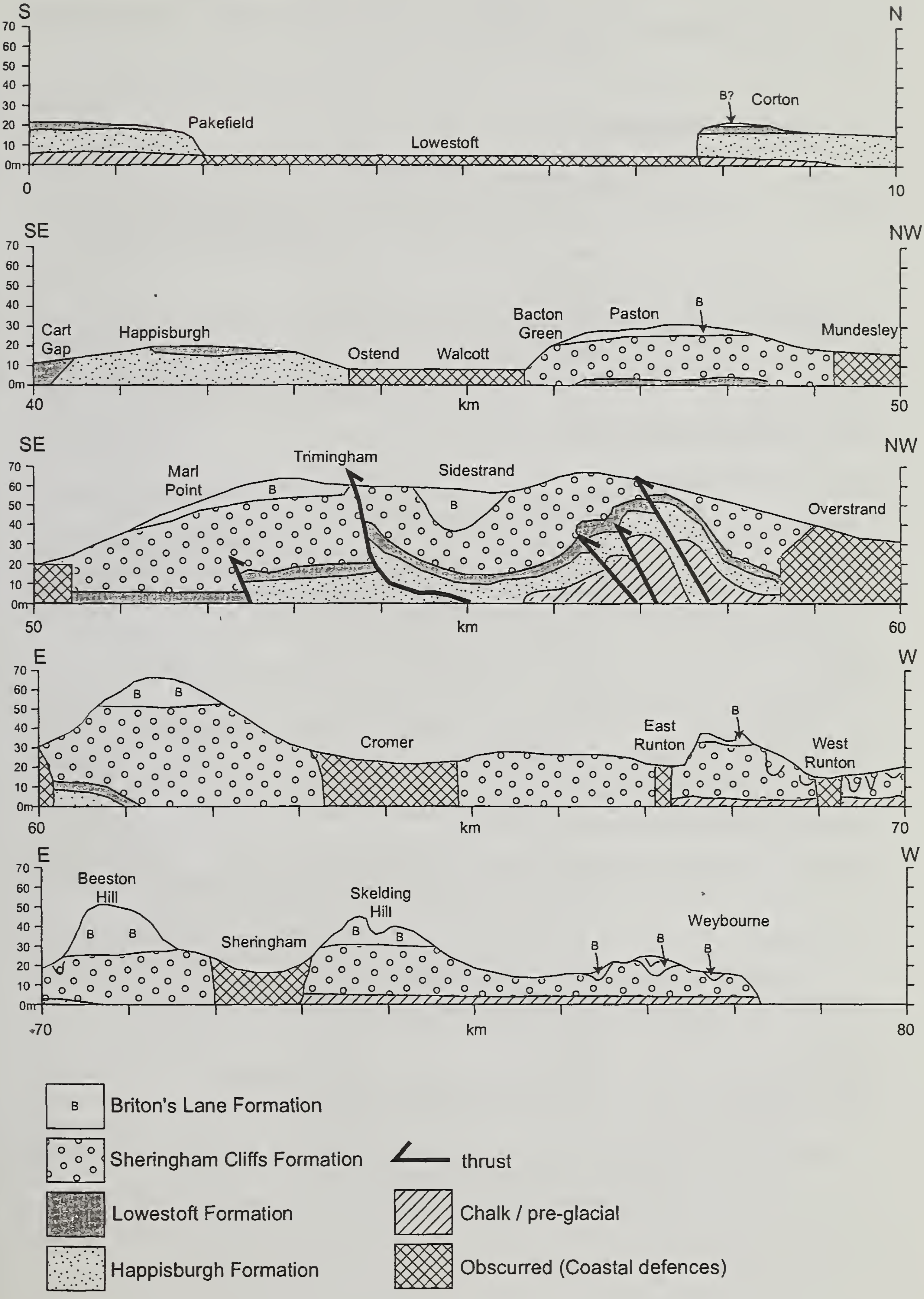
S
N
70
60
50
40
30
20
10
0m
B?
Corton
Pakefield
Lowestoft
0
10
SE
NW
Cart Gap
Happisburgh
Ostend
Walcott
Bacton Green
Paston
B
Mundesley
40
km
50
SE
NW
Marl Point
Trimingham
Sidestrand
Overstrand
B
50
km
60
E
W
B
Cromer
East Runton
West Runton
60
km
70
E
W
Beeston Hill
Skelding Hill
Sheringham
Weybourne
B
-70
km
80
B Briton's Lane Formation
Sheringham Cliffs Formation
Lowestoft Formation
Happisburgh Formation
thrust
Chalk / pre-glacial
Obscurred (Coastal defences)

Table 4. Stratigraphical summary table showing the members of the Happisburgh Formation. Key to sources for previous stratigraphical terms: [1]Blake (1890), [2]Arthurton *et al.* (1994), [3]Hopson & Bridge (1987), [4]Rose *et al.* (1999, 2002), [5]Lunkka (1994), [6]Banham (1968).

CALIFORNIA TILL MEMBER

Stratotype:	TG 518149 – California Gap
Lithofacies:	Stratified diamicton complex consisting of beds of sand (Corton Sand Member material) and brown sandy diamicton (Corton Till Member Material); fold noses and intra-formational sand lenses common
Lower contact:	Unknown
Thickness:	Maximum observed thickness of 13m at California Gap
Genesis:	Subaqueous flow till
Provenance:	British – based on association with Corton Till Member
Section outcrops:	Coastal sections between California Gap and Scratby
Previous stratigraphic terms:	None

CORTON SAND MEMBER

Stratotype:	TM 543979 – Corton Cliffs
Lithofacies:	Stratified sands with common comminuted chalk and shell grains; ice wedge casts and calcretes have also been recognised
Lower contact:	Erosive when overlying Corton Till Member, conformably when overlying Leet Hill Sand and Gravel Member
Thickness:	Commonly between 3-15m
Genesis:	Distal glaciofluvial outwash, tidal-influence in places
Provenance:	British
Section outcrops:	Coastal sections between Pakefield at Happisburgh
Previous stratigraphic terms:	[2,3]Corton Sands

LEET HILL SAND AND GRAVEL MEMBER

Stratotype:	TM 384926 – Leet Hill Quarry, Kirby Cane
Lithofacies:	Channelled and stratified sands and gravels that are rich in flint; common erratic lithologies of British provenance
Lower contact:	Conformable lower contact with underlying Bytham River deposits at stratotype; more commonly erosional contact with Corton Till Member and other pre-glacial sediments
Thickness:	Thickens westwards to up to 9m in the vicinity of the stratotype
Genesis:	Proximal glaciofluvial outwash
Provenance:	British
Section outcrops:	Coastal sections include Corton and Pakefield
Previous stratigraphic terms:	[4]Leet Hill Sands and Gravels

CORTON TILL MEMBER

Stratotype:	TM 543979 – Corton Cliffs
Lithofacies:	Brown and sandy flint-rich matrix-supported diamicton, can be either massive or faintly stratified
Lower contact:	Erosional
Thickness:	Between 0.6-3.2m
Genesis:	Variable – subglacial or subaqueous flow till
Provenance:	British
Section outcrops:	Corton, California Gap and Happisburgh
Previous stratigraphic terms:	[3]Norwich Brickearth, [2,4]Corton Till / Diamicton

HAPPISBURGH SAND MEMBER

Stratotype:	TG 388306 – Happisburgh Cliffs adjacent to lighthouse
Lithofacies:	Stratified sands with channel structures within upper horizons
Lower contact:	Erosional contact with the Ostend Clay Member
Thickness:	8m
Genesis:	Deltaic
Provenance:	-
Section outcrops:	Cliffs between Happisburgh Coastguard Station and Happisburgh lighthouse
Previous stratigraphic terms:	[5]Happisburgh Sands, [6]Intermediate Beds

OSTEND CLAY MEMBER

Stratotype:	TG 388306 – Happisburgh Cliffs adjacent to lighthouse
Lithofacies:	Stratified diamicton and sorted sediments occupying the troughs between ridges on the upper surface of the Happisburgh Till Member; grade upwards into rhythmically-bedded silts and clays with occasional ripples
Lower contact:	Conformable lower contact with Happisburgh Till Member
Thickness:	Maximum thickness of 3.5m
Genesis:	Initial deposition within small pools between till ridges, progressive expansion and coalescence into larger pools and an extensive glacial lake basin
Provenance:	-
Section outcrops:	Ostend cliffs southwards to Happisburgh lighthouse
Previous stratigraphic terms:	[5]Happisburgh Clays, [6]Intermediate Beds

HAPPISBURGH TILL MEMBER

Stratotype:	TG 389305 – Happisburgh Cliffs adjacent to lighthouse
Lithofacies:	Grey, massive matrix-supported diamicton with a sandy matrix texture and common flint and quartzose pebbles
Lower contact:	Erosive
Thickness:	2-7m
Genesis:	Subglacial deforming-bed till
Provenance:	British
Section outcrops:	Coastal sections between Happisburgh lighthouse and Ostend, and Marl Point Trimingham to Overstrand
Previous stratigraphic terms:	[6]First Cromer Till, [5]Happisburgh Diamicton

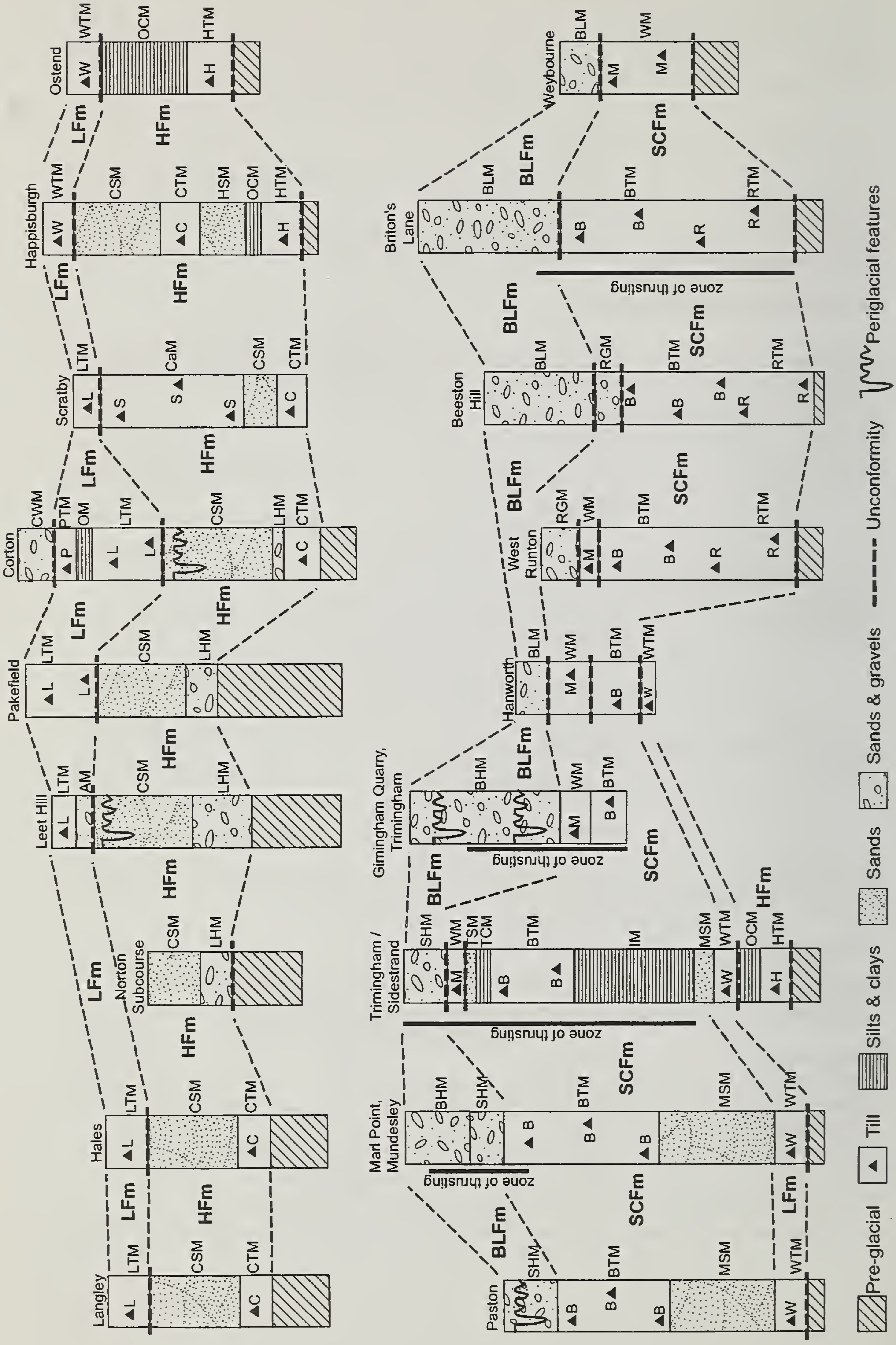
Langley
Hales
Norton Subcourse
Leet Hill
Pakefield
Corton
Scratby
Happisburgh
Ostend
Paston
Marl Point, Mundesley
Trimingham / Sidestrand
Gimingham Quarry, Trimingham
Hanworth
West Runton
Beeston Hill
Briton's Lane
Weybourne
LFm
HFm
BLFm
SCFm
zone of thrusting
LTM
CSM
CTM
LHM
AM
PTM
OM
CWM
CaM
HSM
OCM
HTM
WTM
SHM
BTM
MSM
BHM
WM
TSM
TCM
IM
BLM
RGM
RTM
Pre-glacial
Till
Silts & clays
Sands
Sands & gravels
Unconformity
Periglacial features

Fig. 5. (facing page) A series of composite stratigraphical logs (not to scale) from key sections and boreholes in the study area showing the distribution of members and formations. Abbreviations to formation names: HFm – Happisburgh Formation; LFm – Lowestoft Formation; SCFm – Sheringham Cliffs Formation; BLFm – Briton's Lane Formation. Abbreviations to member names: HTM – Happisburgh Till Member; OCM – Ostend Clay Member; HSM – Happisburgh Sand Member; CTM – Corton Till Member; LHM – Leet Hill Sand and Gravel Member; CSM – Corton Sand Member; CaM – California Till Member; LTM – Lowestoft Till Member; WTM – Walcott Till Member; OM – Oulton Clay Member; PTM – Pleasure Gardens Till Member; AM – Aldeby Sand and Gravel Member; MSM – Mundesley Sand Member; IM – Ivy Farm Laminated Silt Member; RTM – Runton Till Member; BTM – Bacton Green Till Member; TCM – Trimingham Clay Member; TSM – Trimingham Sand Member; WM – Weybourne Town Till Member; RGM – Runton Sand and Gravel Member; SHM – Stow Hill Sand and Gravel Member; BHM – Beacon Hill Sand and Gravel Member; BLM – Briton's Lane Sand and Gravel Member; CWM – Corton Woods Sand and Gravel Member.

metamorphic erratics were observed, and all other rocks that could be attributed to Scandinavia could equally have been derived from Scotland (Lee *et al.*, 2002). Detailed examination of the matrix composition further refines the source areas for the till with palynomorphs from the Lower, Middle and Upper Jurassic plus the Lower Cretaceous Speeton Clay Formation suggesting an additional input of sediment from the area of the Cleveland Basin and the adjacent offshore region (Lee *et al.*, 2002; c.f. Lowestoft Till Member). This is supported by an abundance of amphibole, epidote and garnet non-opaque heavy minerals relative to total opaques (Table 6), since these heavy mineral species are diagnostic of derivation from the reworking of Palaeogene and / or Early Pleistocene sands in the North Sea (Perrin *et al.*, 1979; Lee *et al.*, 2004).

Ostend Clay Member

The Ostend Clay Member corresponds to the Happisburgh Clays of Lunkka (1994) and the lower parts of the Intermediate Beds of Banham (1968). Between Happisburgh (TG 388304) and Ostend (TG 368322), and Trimingham (TG 288387) and Cromer (TG 230417) it infills the upper surface topography of the Happisburgh Till Member forming

		Reworked Sedimentary						Reworked Igneous and Metamorphic				
Source	N	Reworked Pleistocene	Cretaceous	Jurassic	Permo-Triassic	Carbonif-erous	Devonian	Scotland	N.England / Scotland	Scandinavia	Unknown	Unknown
SHERINGHAM CLIFFS FORMATION												
Weybourne Town Till Member												
T – 1	546	7.2	92.8	0.0	0.0	0.0	0.0	3.7	0.0	0.0	0.0	0.0
WT - 1	1009	15.3	83.6	0.1	0.6	0.0	0.0	0.4	0.0	0.0	0.0	0.2
Bacton Green Till Member												
BG – 1	1824	75.0	16.7	2.0	1.8	0.0	0.0	2.3	0.2	0.0	0.0	1.8
T – 1	558	88.1	5.2	0.0	0.0	0.0	1.0	3.7	0.0	0.0	0.0	0.0
Be – 1	503	91.6	7.4	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.5
Runton Till Member												
Be – 1	1292	69.9	20.5	1.8	0.8	0.0	0.0	3.2	0.2	0.0	0.0	2.2
LOWESTOFT FORMATION												
Walcott Till Member												
Ha – 1	809	49.6	42.9	3.2	0.6	0.3	0.3	2.3	0.1	0.0	0.0	0.6
T – 1	893	39.0	59.8	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.2
Hn – 1	481	54.4	46.8	0.4	0.0	0.0	0.2	1.0	0.2	0.0	0.0	0.0
Lowestoft Till Member												
C – 1	3310	8.5	82.7	8.2	0.0	Tr	0.0	0.2	0.0	0.0	0.0	0.3
HAPPISBURGH FORMATION												
Corton Till Member												
Ha – 2	619	82.7	8.9	1.3	0.0	1.1	0.6	4.4	0.0	0.0	0.0	1.0
C – 2	1109	91.1	3.7	3.3	0.0	0.0	0.2	0.6	0.0	0.0	0.0	1.1
Happisburgh Till Member												
T – 2	769	68.1	22.8	1.7	0.4	0.4	0.4	3.5	0.8	0.0	0.0	2.1
Ha – 2	985	65.0	15.7	4.3	1.1	1.4	1.1	5.1	0.5	0.0	2.8	2.4

Table 5. (facing page) Clast content of the till members in the study area. Clast counts were performed on the 4-8mm gravel fraction. Expansion of clast lithology headings: Reworked Pleistocene – brown and white flint, vein quartz, chatter-marked flint, quartzose lithologies, *Rhaxella* chert, Carboniferous chert, Greensand chert, shell, wood; Cretaceous – chalk, black flint, Carstone, glauconitic sandstone; Jurassic – sandstone, limestone (including oolitic types), ironstone, shell; Permo-Triassic – red sandstone (brick red), evaporite, Magnesian limestone; Carboniferous – coal, limestone, ironstone; Devonian – red sandstone; Scottish crystalline – Dalradian metasediments, olivine and porphyritic basalt, acid porphyry, andesite, granitoids; Northern England / Scotland – quartz dolerite / basalt, Cheviot granite; Scandinavia – rhomb porphyry, larvikite, nordmarkite, high-grade metamorphic. Key to abbreviations: Ha – Happisburgh, T – Trimingham, Hn – Hanworth, C – Corton, Be – Beeston, WT – Weybourne Town Pit, WC – Weybourne Cliffs. Source: 1 – Lee (2003), 2 – Lee *et al.* (2002), 3 – Pawley *et al.* (2004).

a series of onlapping beds that reach a maximum thickness of 3.5m. These beds consist of stratified diamicton at the base, that grades upwards into rhythmically-laminated silts and clays with occasional isolated sand ripples, and convoluted horizons. They represent ice-marginal glaciolacustrine sedimentation.

Happisburgh Sand Member

The Happisburgh Sand Member crops out between the Ostend Clay Member and the Corton Till Member at Happisburgh (TG 390305) where it reaches a maximum observed thickness of 8m and corresponds to the Happisburgh Sands of Lunkka (1994). It consists of yellowish brown (10YR 5/8) and yellow-orange (10YR 7/3) sands and rests on the scoured upper surface of the Ostend Clay Member. Structurally it exhibits massive bedding, ripples, horizontal beds, channel structures and sporadic horizons of convolute bedding. Planar cross-beds are also common with palaeocurrent directions indicating localised flow towards the southeast. They have been interpreted as delta bottom-sets and delta top-sets (Hart, 1999; Lunkka, 1988; Lee, 2003).

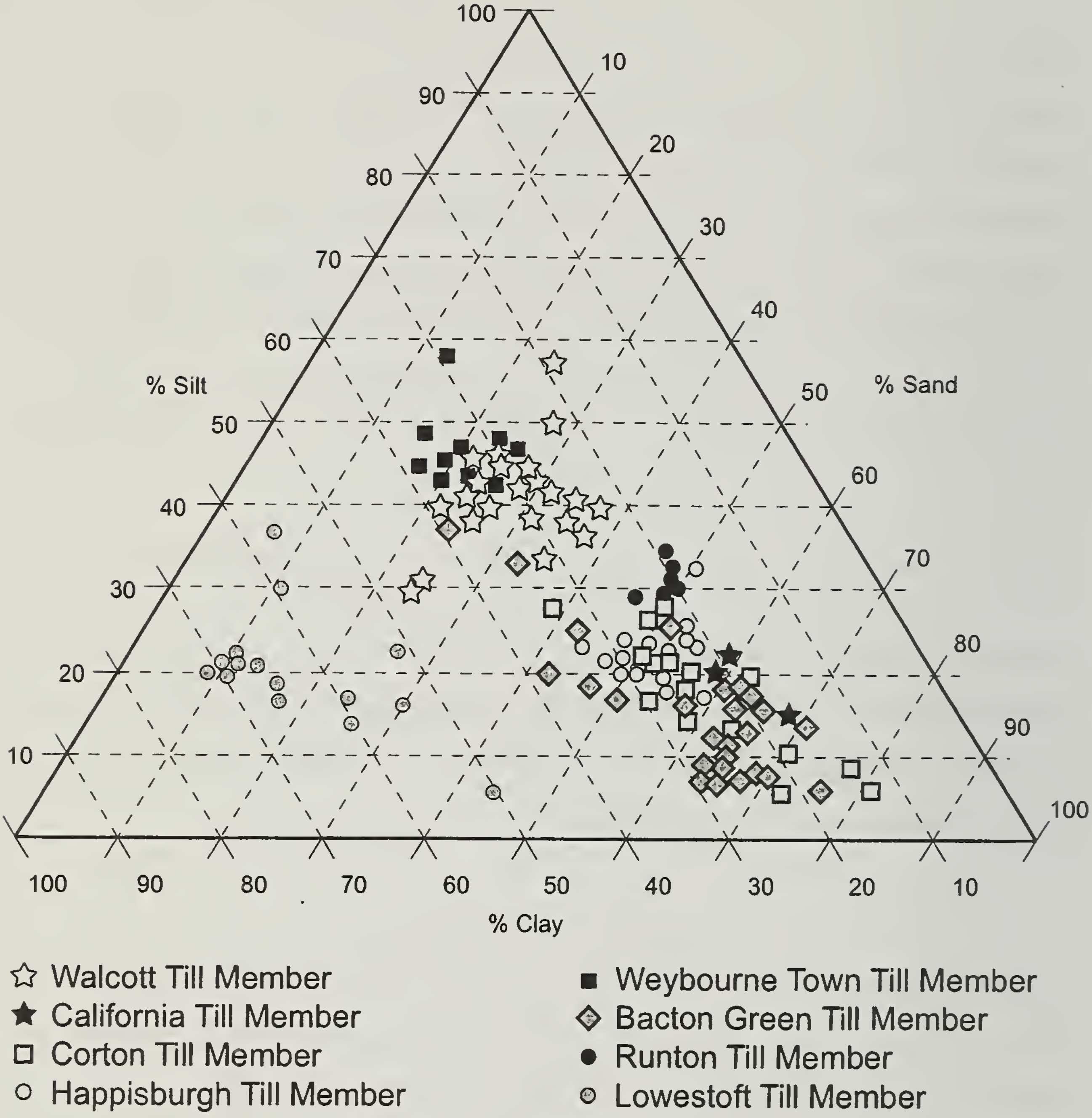

Fig. 6. Ternary diagram showing the particle size properties of the matrix (sand-silt-clay) of the till units within the study area. Measurement involved a combination of wet and dry sieving for the >63μm sand fraction and by the Sedigraph method for the <63μm silt and clay fractions.

Table 6. Mean heavy mineral composition (at one standard deviation) of units within the Happisburgh Formation. Analysis was performed on the 63-125μm fine sand fraction which proved the most diagnostic sub-fraction for discriminating between units. Heavy mineral separation and counting were undertaken using standard procedures (Gale & Hoare, 1991), with between 500-700 grains counted per sample.

	Happisburgh Till Member	**Happisburgh Sand Member**	**Corton Till Member**	**Leet Hill Sand & Gravel Mem**	**Corton Sand Member**	**California Till Member**
% Opaques	28.8 (2.3)	57.3 (7.9)	29.0 (3.1)	60.0 (8.6)	44.9 (9.8)	29.1 (2.3)
Non-opaques (% of total non-opaques)						
% Amphibole Group	40.2 (1.5)	32.8 (7.0)	39.5 (3.1)	31.8 (7.6)	39.3 (5.2)	38.4 (0.7)
% Apatite	2.7 (0.6)	1.9 (0.8)	1.6 (0.6)	7.2 (2.8)	1.7 (1.5)	1.5 (0.3)
% Epidote	23.7 (2.8)	21.6 (3.7)	23.4 (2.3)	18.2 (3.6)	22.1 (3.9)	23.0 (2.0)
% Garnet	15.6 (2.1)	21.4 (8.7)	17.4 (2.5)	17.3 (8.1)	18.3 (3.8)	18.7 (1.0)
% Kyanite	0.9 (0.4)	0.4 (0.4)	1.0 (0.4)	0.9 (0.9)	0.8 (0.6)	1.9 (0.4)
% Mica	1.5 (0.8)	2.2 (2.0)	1.9 (0.6)	2.3 (1.3)	1.8 (1.2)	3.3 (1.4)
% Pyroxene	3.4 (1.5)	2.0 (1.7)	1.3 (0.6)	2.7 (1.0)	1.4 (1.0)	1.9 (0.6)
% Rutile	0.8 (0.3)	2.8 (0.8)	1.3 (0.5)	1.5 (0.9)	1.4 (1.0)	0.9 (0.3)
% Staurolite	0.2 (0.2)	0.6 (0.2)	0.1 (0.1)	0.9 (0.6)	0.7 (0.6)	0.2 (0.2)
% Tourmaline	4.0 (1.0)	3.5 (1.0)	3.6 (1.4)	6.3 (2.5)	4.1 (1.9)	2.9 (0.6)
% Zircon	4.9 (1.5)	8.4 (1.9)	6.6 (2.2)	8.5 (5.0)	6.8 (3.6)	7.0 (1.3)
% Other	2.2 (0.8)	2.4 (1.5)	2.5 (0.8)	2.4 (1.1)	1.8 (1.3)	1.4 (0.2)
Number of samples	14	5	15	15	39	4

Table 7. Calcium carbonate content of the matrix from the major till units.

	Mean % $CaCO_3$	**Number of samples**
Weybourne Town Till Member	68.7	11
Bacton Green Till Member	11.3	15
Runton Till Member	14.7	5
Lowestoft Till Member	32.1	20
Walcott Till Member	36.2	15
Corton Till Member	8.4	15
Happisburgh Till Member	12.3	14

Corton Till Member

This member has been mapped extensively throughout the Lowestoft, Great Yarmouth and North Walsham districts and crops out in coastal sections at Corton (TM 543979), California Gap (TG 518148) and Happisburgh (TG 390305). In its southern outcrop, it rests unconformably on shallow marine deposits of the Wroxham Crag Formation (Hopson & Bridge, 1987; Arthurton *et al.*, 1994; Rose *et al.*, 2002) and has been referred to as the Norwich Brickearth (Bridge & Hopson, 1985; Hopson & Bridge, 1987), Cromer Till (Banham, 1971) or Corton Till (Arthurton *et al.*, 1994). Further north at Happisburgh, the deposit has a gradational lower contact with the Happisburgh Sand Member (Lee, 2003). It consists of a light olive-brown (2.5Y 5/4) to olive-brown (2.5YR 4/4) matrix-supported sandy (Fig. 6), clast-poor diamicton (<1%) that attains a maximum observed thickness of 3.2m. Two distinctive facies occur, firstly, at California Gap the diamicton is massive and highly consolidated and interpreted as a subglacial deformation till based largely upon its micro-scale deformation properties (Lee, 2003). Secondly, at Corton the diamicton is crudely stratified commonly exhibiting sandy stringers, dewatering structures, isoclinal fold noses showing a direction of overturn towards the southeast, and inter-stratified beds of waterlain sediment and subglacial till; it is interpreted as a series of subaqueous flow tills representing a grounding-line position (Lee, 2001) associated with a receding ice margin (Lee, 2003). An intermediate facies crops out at Happisburgh, with a massive lower facies becoming stratified progressively upwards.

Lithologically, the till is strikingly similar to the Happisburgh Till Member in terms of particle size distribution (Fig. 6), calcium carbonate (Table 7) and heavy mineral content (Table 6). The clast composition is, however, different with the Corton Till Member containing higher proportions of re-worked Pleistocene lithologies such as flint, vein quartz and quartzite relative to chalk-derived clasts (Table 5) (Lee *et al.*, 2002).

Additional features that allow discrimination between the two tills are the brown coloration, frequent stratified structure and lower apatite content of the Corton Till Member. Provenance-diagnostic lithologies are less abundant than within the Happisburgh Till Member, but similarities of clast and palynomorph assemblages demonstrate that the Corton Till Member is also of British derivation (Lee *et al.*, 2002).

Leet Hill Sand and Gravel Member

The Leet Hill Sand and Gravel Member consists of stratified and channelled proximal glaciofluvial outwash deposits that have been mapped extensively through the Lowestoft and Yarmouth districts. It is traced in this area through numerous boreholes (Hopson & Bridge, 1987; Rose *et al.*, 2002), as well as being exposed at coastal sections and quarries at Leet Hill (TM 384962), Pakefield (TM 537892), Corton (TM 543979) and Norton Subcourse (TM 402995) (Rose *et al.*, 1999a, 2002; Lee, 2003). Reconstruction of the sub-surface geometry of these gravels using borehole evidence demonstrates that they thicken progressively westwards from Corton (up to 0.8m) to around 9m in the vicinity of Leet Hill (Hopson & Bridge, 1987). Lithologically, the gravels are rich in flint (66.4-79.8%) and quartzose (19.3-31.3%) clasts, but contain far-travelled erratics of northern provenance including Old Red Sandstone, basaltic porphyry, dolerite and Carboniferous Limestone (Table 8) (Rose *et al.*, 1999a, 2002; Lee, 2003). In terms of the heavy mineral composition of the fine sand fraction, they can be distinguished from all other non-diamicton units by their high relative apatite (7.2% ± 2.8) content (Table 6). At their Leet Hill stratotype, the sands and gravels are a transitional lithofacies between underlying fluvial terrace deposits of the Bytham river (Kirby Cane Sands and Gravels) and the overlying Corton Sand Member (Happisburgh Formation) (Lee *et al.*, 2004). At other localities such as Corton and Pakefield, the sands and gravels are incised into either the Corton Till Member or shallow marine Crag deposits (Hopson & Bridge, 1987; Arthurton *et al.*, 1994; Lee, 2003). Palaeocurrent measurements indicate that initial drainage was controlled by the pre-existing Bytham river valley topography. Upon infilling of this valley system by outwash, drainage was diverted southwards, unconstrained by topography (Rose *et al.*, 1999a; Lee, 2001).

Source	n	**Carb-onifer ous chert**	Triassic				Jurassic			Cretaceous						Tert-iary / Pleis. ch. mkd flint	**Total Flint**	Ign, Met, Sed		**Unk-nown**
			Qtz-ite	vein qtz	schorl	**Total**	Rhax-ella Chert	sst, lst, irnst, shell	**Total**	sst, lst, irnst, shell	glauc-onitic sstn	Green-sand chert	Chalk	Flint	**Total**			Scot / N'th-ern	Scand-inavia	
BRITONS LANE FORMATION																				
Briton's Lane Sand and Gravel Member																				
WC3	668	**0.7**	2.7	4.3	1.0	**8.0**	1.0	0.4	**1.4**	0.1	0.0	0.0	0.0	80.1	**80.2**	5.5	**85.6**	2.7	0.1	**0.7**
BL1	2141*	**0.1**	3.7	5.8	0.3	**9.7**	0.6	0.3	**0.9**	0.0	0.0	0.7	0.0	80.8	**81.5**	6.3	**87.1**	2.0	0.0	**0.0**
BL2	1863	**0.7**	8.2	1.5	0.6	**10.3**	1.3	0.0	**1.3**	5.6	0.0	0.0	0.0	57.0	**62.6**	19.9	**81.9**	4.7	0.1	**0.4**
HA1	872*	**0.0**	5.5	7.2	0.0	**12.7**	1.0	0.6	**1.6**	0.0	0.0	0.4	0.0	74.2	**74.6**	9.6	**83.8**	1.5	0.0	**0.0**
WR1	490	**0.0**	3.1	7.0	0.1	**10.2**	0.5	0.0	**0.5**	0.4	0.0	0.4	0.0	79.9	**80.7**	7.4	**87.3**	1.2	0.0	**0.2**
Beacon Hill Sand and Gravel Member																				
GQ1	1207*	**0.0**	1.1	9.7	0.2	**11.0**	0.3	0.2	**0.5**	1.2	0.0	0.9	0.0	80.1	**82.2**	6.5	**86.6**	0.3	0.0	**0.1**
Stow Hill Sand & Gravel Member																				
PS1	576	**0.0**	1.3	3.3	1.9	**6.5**	1.2	0.0	**1.2**	0.4	0.2	0.5	0.0	85.6	**86.7**	4.5	**90.1**	1.0	0.0	**0.0**
SD1	992*	**0.0**	0.8	5.4	0.2	**6.4**	0.3	0.2	**0.5**	0.0	0.0	0.6	0.0	85.4	**86.0**	6.6	**92.0**	0.3	0.0	**0.0**
SHERINGHAM CLIFFS FORMATION																				
Runton Cliffs Sand and Gravel Member																				
BH1	751	**0.0**	1.5	10.7	0.7	**12.8**	1.6	0.1	**1.7**	0.1	0.0	0.0	0.0	73.8	**73.9**	7.9	**81.6**	3.7	0.0	**0.0**
LOWESTOFT FORMATION																				
Aldeby Sand and Gravel Member																				
LH2	241	**0.4**	5.0	2.1	0.4	**7.5**	0.0	2.5	**2.5**	15.4	0.0	0.0	44.0	29.0	**88.8**	0.4	**29.4**	0.0	0.0	**0.0**
HAPPISBURGH FORMATION																				
Leet Hill Sand and Gravel Member																				
PA1	2993*	**0.2**	5.7	16.4	0.4	**22.6**	0.6	0.4	**1.0**	0.2	Tr	0.9	0.2	55.5	**56.8**	15.9	**71.4**	2.2	0.0	**0.3**
C1	902	**0.6**	4.1	15.8	0.8	**20.7**	0.0	0.6	**0.6**	0.3	0.0	0.7	0.3	61.8	**63.1**	13.7	**75.5**	0.8	0.0	**0.6**
NS1	2611*	**0.1**	10.2	17.9	0.3	**27.6**	0.2	Tr	**0.2**	0.0	0.0	0.8	0.0	59.5	**60.1**	12.0	**71.5**	0.6	0.0	**0.0**
LH2	3756*	**1.0**	7.6	11.9	0.9	**20.4**	0.6	0.3	**0.9**	1.2	Tr	0.2	3.0	58.5	**63.0**	13.3	**71.9**	0.0	0.9	**0.3**

Table 8. (facing page) Lithological composition of outwash gravels. The 8-16mm size fraction prove the most diagnostic in terms of quantifying bulk lithology; however, many of the diagnostic lithologies used for provenancing are cobble-sized clasts. Abbreviation of Source: LH – Leet Hill, NS – Norton Subcourse, C – Corton, PA – Pakefield, WR – West Runton, SD – Sidestrand, PS – Paston, GQ – Gimingham Quarry, Trimingham, HA – Hanworth, BH – Beeston Hill, BL – Britons Lane, WC – Weybourne Cliffs, 1 – from Lee (2003), 2 – from Rose *et al.* (1999), 3 – from Pawley *et al.* (2004). * indicates aggregate values from multiple samples.

Corton Sand Member

The Corton Sand Member reaches thicknesses of 15m throughout the Lowestoft, Yarmouth and North Walsham districts where it is widely distributed. It rests upon either the Corton Till Member, as at Corton (TM 540985), California (TG 520144) and Happisburgh (TG 390303), or the Leet Hill Sand and Gravel Member at localities including Norton Subcourse (TM 402995), Pakefield (TM 537892) and Leet Hill (TM 384962). It is composed of pale yellow (2.5Y 8/4) chalky and shelly (detrital) sands that exhibit a variety of types of cross-bedding, ripples, horizontal and massive bedding, and soft-sediment deformation structures (e.g. convolute bedding, flame structures). Genetically, the sedimentology of the sands is typical of a progressively distal glaciofluvial environment during deglaciation (Hopson & Bridge, 1987; Lee, 2003). The heavy mineral composition of the sands exhibits a moderate degree of spatial variability; however, they can still be readily identified across their distribution area (Table 6).

Cryoturbation features and ice-wedge pseudomorphs have been reported from Corton and Burgh Castle (Ranson, 1968b; Bridge & Hopson, 1985; Arthurton *et al.*, 1994), whilst a rhizogenic calcrete has been identified at Leet Hill (Candy, 2002). Elsewhere in the literature, they have been referred to as the Corton Beds (Banham, 1971) or the Corton Sands (Bridge & Hopson, 1985; Rose *et al.*, 1999a, 2002).

California Till Member

The California Till Member has a localised outcrop in coastal sections within the Scratby and California Gap area (TG 521143) where it rests conformably upon the Corton Sand Member. The unit attains a maximum thickness of 13m and consists of beds of massive and faintly stratified olive brown (2.5YR 4/4) sandy diamicton (Fig. 6), separated by

Table 9. Stratigraphical summary table showing the members of the Lowestoft Formation. Abbreviations to sources for previous stratigraphical terms: [1]Rose *et al.* (1999, 2002), [2]Arthurton *et al.* (1994), [3]Hopson & Bridge (1987), [4]Baden-Powell (1948), [5]Lunkka (1994), [6]Banham (1968, 1971).

ALDEBY SAND AND GRAVEL MEMBER

Stratotype:	TM 384926 – Aldeby Quarry, Aldeby
Lithofacies:	Chalk-rich stratified sands and gravels
Lower contact:	Erosional
Thickness:	Up to 4m
Genesis:	Proximal glaciofluvial outwash
Provenance:	British
Section outcrops:	Aldeby Quarry, Scratby
Previous stratigraphic terms:	[1]Aldeby Sands and Gravels

PLEASURE GARDENS TILL MEMBER

Stratotype:	TM 546987 – Corton Woods, Corton
Lithofacies:	Stratified diamicton complex composed of beds of Lowestoft Till Member and Oulton Clay Member material
Lower contact:	Inter-bedded with Oulton Clay Member
Thickness:	0.9m
Genesis:	Subaqueous flow till
Provenance:	British
Section outcrops:	Limited exposure at stratotype locality
Previous stratigraphic terms:	Pleasure Gardens Till

OULTON CLAY MEMBER

Stratotype:	TM 546987 – Corton Woods, Corton
Lithofacies:	Horizontally-laminated light grey sandy silts and grey clays with occasional isolated light grey sand lenses
Lower contact:	Conformable with Lowestoft Till Member
Thickness:	Maximum observed thickness of 2.2m
Genesis:	Glaciolacustrine
Provenance:	-
Section outcrops:	Limited exposure at stratotype locality
Previous stratigraphic terms:	[2,3]Oulton Beds

WALCOTT TILL MEMBER

Stratotype:	TG 391304 – Ostend
Lithofacies:	Grey, massive, matrix-supported diamicton; rich in chalk clasts and matrix calcium carbonate content; intermediate opaque heavy mineral content between Happisburgh Formation tills and the Lowestoft Till Member
Lower contact:	Erosional
Thickness:	Maximum observed thickness 1.6m
Genesis:	Subglacial deforming-bed till
Provenance:	British – North Sea ice advance from the northwest
Section outcrops:	Cliffs north of Cart Gap, Happisburgh lifeboat station to Ostend, discontinuously from Paston to Overstrand
Previous stratigraphic terms:	[6]Second Cromer Till, [5]Walcott Diamicton

LOWESTOFT TILL MEMBER

Stratotype:	TM 546987 – Corton Woods, Corton
Lithofacies:	Dark grey, clay-rich, massive, matrix-supported diamicton; rich in opaque heavy minerals, chalk clasts and matrix calcium carbonate content
Lower contact:	Erosive
Thickness:	Up to 4m
Genesis:	Subglacial deforming-bed till
Provenance:	British – Pennine ice advance from the west
Section outcrops:	Coastal sections between Pakefield and Corton Woods, also Scratby, California Gap and Leet Hill Quarry
Previous stratigraphic terms:	[1,2,3]Lowestoft Till,[4]Chalky Boulder Clay

massive and horizontal-bedded chalky sand with occasional augen-shaped lenses of fine silty-sand. Isoclinal fold noses are common and show (after correction for tilting) flow towards the south and southeast. The composition of these diamicton and sand beds is identical to that of the Corton Till and Corton Sand members respectively and suggests that these deposits form the parent material of the California Till Member. The California Till Member is interpreted as a subaqueous flow till.

Lowestoft Formation

The Lowestoft Formation (stratotype: Corton near Lowestoft – TM 5496) (Table 9) is based on the Lowestoft Till Member of the Lowestoft and Yarmouth districts which can be correlated laterally with the Walcott Till Member of the North Walsham, Mundesley and Cromer districts (Figs 3, 4 & 5). A disconformity is present between the Happisburgh and Lowestoft formations throughout the region. The spatial variation in the elevation of this disconformity suggests that between 15-25m of Happisburgh

Formation material was eroded prior-to, and during, the onset of periglacial conditions before the arrival of ice that deposited the Lowestoft Formation.

Lowestoft Till Member

The stratotype of the Lowestoft Till Member is the coastal sections around Corton (TM 546987) near Lowestoft. From Corton, the unit formerly referred to as either the Lowestoft Till (Banham, 1971; Bridge & Hopson, 1985) or Chalky Boulder Clay (Baden-Powell, 1948, West & Donner, 1956), is mappable across the Lowestoft and Yarmouth districts where it truncates the Corton Sand Member or California Till Member. Localities where the till can be observed in section include Corton, Pakefield (TM 536884), Scratby (TG 514156), California Gap (TG 517148) and Leet Hill (TM 384962), and previously Aldeby (TM 459928). The unit is up to 4m thick, and consists of a dark grey, clay-rich, matrix-supported diamicton (Fig. 6), that is massive in structure, and has been interpreted as a subglacial deformation till (Hart *et al.*, 1990; Richards, 2000).

One of the most striking features of the till is its distinctive range of lithological properties – specifically, a moderate matrix calcium carbonate content (Table 7); palynomorphs from the matrix are almost exclusively derived from the Kimmeridge Clay Formation (Riding, 2002); a high proportion of chalk and black flint clasts are from the Chalk Group (Table 5) (Lee, 2003); the heavy mineral composition of the sand fraction contains high opaque concentrations (mainly limonite) and apatite derived from ironstone horizons within Jurassic and Lower Cretaceous mudstones (Table 10) (Lee, 2003). These lithological properties demonstrate that the ice that deposited the Lowestoft Till Member entered the region from the west crossing the Fenland Basin (Kimmeridge Clay Formation) and Chalk escarpment. This is consistent with clast fabric and shear plane measurements from Corton and Pakefield, and other published sites (West & Donner, 1956; Perrin *et al.*, 1979; Rose, 1992; Fish & Whiteman, 2001; Lee, 2003).

Walcott Till Member

In the North Walsham, Mundesley and Cromer districts, the basal member of the Lowestoft Formation is the Walcott Till Member which is equivalent to the Second Cromer Till of Banham (1968) or Walcott Diamicton of Lunkka (1994). The unit crops out in coastal sections between Happisburgh (TG 380313) and Cromer (TG 234414) where it reaches a maximum observed thickness of 1.6m. Its base is marked by a décollement surface upon Happisburgh Formation sediments or shallow marine Wroxham Crag deposits (Paston – Marl Point, Trimingham). It has also been mapped in the North Walsham district where it overlies the Corton Sand Member of the Happisburgh Formation and forms a mapping continuity with the Lowestoft Till Member of the Great Yarmouth and Lowestoft areas. It consists of an olive-grey (2.5Y 5/1) to olive-brown (2.5Y 4/3) silt-rich matrix-supported diamicton (Fig. 6) that is largely massive in structure. It has a moderate calcium carbonate matrix content (Table 7) and has been interpreted as a subglacial till with clast fabric and shear plane measurements indicating ice flow from the northwest (Banham, 1968, 1988; Lunkka, 1994; Lee, 2003).

The till exhibits a broadly intermediate lithology between the Happisburgh Till Member and Lowestoft Till Member: broadly equal proportions of clasts derived from Cretaceous bedrock (chalk and black flint) and reworked Pleistocene deposits (vein quartz, quartzite, other types of flint) (Table 5) (Lee, 2003); a palynomorph association that contains Pliensbachian and Toarcian (Lower Jurassic) forms derived from the Whitby Mudstone Formation, in addition to Kimmeridgian forms from the Kimmeridge Clay Formation (Riding, 1999); heavy mineral composition that contains lower quantities of opaques and non-opaque minerals such as apatite typical of the Lowestoft Till Member, relative to higher proportions of amphibole, epidote and garnet characteristic of the Happisburgh Till Member (Table 10) (Lee, 2003). In addition the Walcott Till Member contains diagnostic lithologies unique to a British provenance including several *Gryphaea* shells derived from the Lower Lias (Jurassic), and clasts of Magnesian Limestone, Carboniferous Limestone and palynomorphs from Viséan to Westphalian strata.

Oulton Clay Member

The Oulton Clay Member (Oulton Beds of Banham (1971)) rests conformably upon the upper surface of the Lowestoft Till Member beneath Corton Woods (TM 546987) where it locally crops out and reaches a maximum observed thickness of 2.2m. It is composed of horizontally-laminated light grey (2.5Y 7/2) sandy silts and grey (5Y 5/1) clays with occasional isolated light grey (2.5Y 7/1) sand lenses. It has been interpreted as a localised glaciolacustrine deposit (Pointon, 1978; Bridge & Hopson, 1985).

Table 10. Mean heavy mineral composition (at one standard deviation) of units within the Lowestoft Formation. Analysis was performed on the 63-125μm fine sand fraction.

	Lowestoft Till Member	**Walcott Till Member**	**Pleasure Gardens Till Member**
% Opaques	55.8 (4.0)	36.7 (3.3)	48.0 (4.6)
Non-opaques (% of total non-opaques)			
% Amphibole Group	27.7 (2.1)	38.8 (3.3)	29.5 (1.0)
% Apatite	16.4 (6.2)	6.2 (1.0)	16.2 (1.5)
% Epidote	17.0 (2.6)	19.4 (2.0)	16.8 (1.9)
% Garnet	17.8 (4.5)	15.8 (2.9)	13.3 (0.7)
% Kyanite	0.8 (0.3)	1.1 (0.5)	0.5 (0.7)
% Mica	2.3 (1.4)	4.2 (2.4)	7.0 (3.7)
% Pyroxene	1.8 (0.4)	1.6 (0.7)	2.2 (1.1)
% Rutile	1.9 (0.4)	1.0 (0.6)	0.2 (0.2)
% Staurolite	0.3 (0.3)	0.3 (0.5)	0.7 (0.4)
% Tourmaline	4.4 (1.0)	3.3 (1.1)	3.0 (0.3)
% Zircon	8.1 (1.6)	5.3 (1.7)	7.9 (0.3)
% Other	1.6 (0.8)	3.0 (1.2)	2.6 (1.7)
Number of samples	20	15	3

Pleasure Gardens Till Member (PTM)

Cropping-out above the Oulton Clay Member beneath Corton Woods (TM 546987) is a second, highly localised unit, the Pleasure Gardens Till Member. The unit is up to 0.9m thick and consists of a contorted melange of Lowestoft Till Member and Ostend Member material. It has been interpreted as a flow till (Banham, 1971; Pointon, 1978). Deformation structures within the till are considered to represent sub-horizontal mixing during flow, and load-induced dewatering.

Aldeby Sand and Gravel Member

The Aldeby Sand and Gravel Member is a chalk-rich glaciofluvial sand and gravel (Table 8) derived from the ice sheet that deposited the Lowestoft Till Member. It crops out locally at Aldeby TM (459928), Leet Hill (TM 384962) and Scratby (TG 415156) and was called the Aldeby Sands and Gravels by Rose *et al.* (1999a).

Sheringham Cliffs Formation

The stratotype for the Sheringham Cliffs Formation is the coastal sections between West Runton (TG 1843) and Skelding Hill (TG 1443) to the west of Sheringham. Sheringham Cliffs Formation sediments correspond to the 'Third Cromer Till' of Banham (1968), the highly calcareous till or 'Marly Drift' of the Cromer area, and all associated outwash deposits (Table 11). They are exposed in coastal sections between Bacton Green (TG 334350) and Weybourne (TG 1143) and have been mapped extensively inland (Figs 3, 4 and 5).

Three tills are recognised within the West Runton and Sheringham area (Fig. 5). The lower two tills are the Runton and Bacton Green Till members (Lee, 2003; Pawley *et al.*, 2004) and these record a transition from subglacial to subaqueous styles of sedimentation. Eastward towards Sheringham and Weybourne, these tills are truncated, and in places have been incorporated subglacially into the Weybourne Town Till Member (Lee, 2003; Pawley *et al.*, 2004). This style of remobilisation and inter-mixing of the separate till units indicates that the Runton and Bacton Green Till members were still relatively water-saturated when the Weybourne Town Till Member was deposited, suggesting that all three tills were laid-down during one glacial episode (Pawley *et al.*, 2004).

Table 11. Stratigraphical summary table showing the members of the Lowestoft Formation. Abbreviations to sources for previous stratigraphical terms: [1]Banham (1968), [2]Lunkka (1994), [3]Hart (1992) / Hart & Boulton (1991a).

RUNTON CLIFFS SAND & GRAVEL MEMBER

Stratotype:	TG 180432 – Beeston Cliffs, West Runton
Lithofacies:	Stratified sands with gravel seams
Lower contact:	Sharp
Thickness:	Up to 10m
Genesis:	Proximal outwash
Provenance:	British
Section outcrops:	East Runton – Sheringham
Previous stratigraphic terms:	[1]Gimingham Sands

WEYBOURNE TOWN TILL MEMBER

Stratotype:	TG 114431 – Weybourne Town Pit
Lithofacies:	Matrix-supported chalky diamicton; locally contains inclusions of Runton Till and Bacton Green Till members
Lower contact:	Sharp and erosional; frequent décollement plane
Thickness:	Up to 6m
Genesis:	Subglacial till
Provenance:	British – North Sea ice advance from the NW
Section outcrops:	Trimingham, Gimingham Quarry, West Runton to Weybourne
Previous stratigraphic terms:	[1,2]Marly Drift

TRIMINGHAM SAND MEMBER

Stratotype:	TG 266397 – Trimingham
Lithofacies:	Stratified sands
Lower contact:	Erosional
Thickness:	Up to 30cm
Genesis:	Deltaic
Provenance:	-
Section outcrops:	Trimingham – Sidestrand
Previous stratigraphic terms:	[3]Trimingham Sands

TRIMINGHAM CLAY MEMBER

Stratotype:	TG 266397 – Trimingham
Lithofacies:	Rhythmically bedded silts and clays
Lower contact:	Gradational with Bacton Green Till Member
Thickness:	Approximately 2m
Genesis:	Distal glaciolacustrine
Provenance:	-
Section outcrops:	Trimingham – Sidestrand
Previous stratigraphic terms:	[3]Trimingham Clays

BACTON GREEN TILL MEMBER

Stratotype:	TG 334347 – Bacton Green
Lithofacies:	Stratified diamicton complex composed of beds of diamicton and sand; fold noses and augen structures (within the bedded sands) are common
Lower contact:	Gradational with either Mundesley Sand Member or Runton Till Member
Thickness:	Up to 11m
Genesis:	Subaqueous flow till
Provenance:	British
Section outcrops:	Bacton Green – Mundesley, Trimingham – Overstrand, East Runton – Sheringham
Previous stratigraphic terms:	[1]Third Cromer Till, [3]Mundesley Diamicton

RUNTON TILL MEMBER

Stratotype:	TG 180432 – Beeston Cliffs, West Runton
Lithofacies:	Highly consolidate matrix-supported diamicton; contains highly sheared inclusions of chalk (pebble to raft size), sand and Walcott Till Member material
Lower contact:	Sharp and erosional; frequent décollement plane
Thickness:	Up to 9m
Genesis:	Subglacial till
Provenance:	British – North Sea ice advance from the NW
Section outcrops:	East Runton – Sheringham
Previous stratigraphic terms:	[3]Laminated Diamicton, [1]Contorted Drift, [2]Cromer Diamicton

IVY FARM LAMINATED SILT MEMBER

Stratotype:	TG 268397 – Sidestrand
Lithofacies:	Rhythmically-bedded clays sand silts, marl and a thin bed of sand
Lower contact:	Gradational
Thickness:	At least 22m
Genesis:	Distal glaciolacustrine
Provenance:	-
Section outcrops:	Trimingham – Sidestrand
Previous stratigraphic terms:	[3]Trimingham Member

MUNDESLEY SAND MEMBER

Stratotype:	TG 325356 – Mundesley
Lithofacies:	Stratified sands, chalky at the base
Lower contact:	Sharp but not erosional
Thickness:	Up to 9m
Genesis:	Deltaic
Provenance:	British
Section outcrops:	Paston – Mundesley, Mundesley to Sidestrand
Previous stratigraphic terms:	[1,2]Mundesley Sands

Mundesley Sand Member

The basal lithofacies of the Sheringham Cliffs Formation is the Mundesley Sand Member (Mundesley Sands of Banham, 1968), which rests upon the upper eroded surface of the Walcott Till Member in north Norfolk. It reaches a maximum thickness of 9m and consists of dull yellow-orange (10YR 6/3) to dull yellowish brown (10YR 5/4) stratified sands with a high abundance of detrital chalk grains within the basal few metres. Typical bedding structures include planar cross-bedding, massive bedding, horizontal bedding, climbing ripples and several horizons of convolute bedding. A distinctive feature of these sands is their high opaque heavy mineral concentrations – typically about 60% (Table 12). They are interpreted as glaciodeltaic in origin on the basis of sedimentology and lithology. The member crops out in coastal sections between Paston (TG 325356) and Trimingham (TG 293383), from where it thins northwards towards Trimingham (TG 277392) before pinching-out beneath the Ivy Farm Laminated Silt Member at Sidestrand (TG 265398).

Ivy Farm Laminated Silt Member

The Ivy Farm Laminated Silt Member rests conformably on the Walcott Till Member at Sidestrand (TG 268397) although towards Trimingham, these two deposits are separated by the Mundesley Sand Member. The true thickness of the member cannot be measured directly because it is truncated by several large-scale basal shear planes; however, reconstructions of the undeformed profile suggest an original thickness of at least 22m. Three distinctive facies assemblages are present. (1) A basal facies up to 6m thick, which consists of rhythmically-bedded dark grey (5Y 3/1) clays and light grey (2.5Y 7/2) silts that grade upwards into a white (5Y 8/2) to pale yellow (5Y 8/2) marl. Contacts between couplets are generally sharp although some gradational-types were noted. The facies is interpreted as an ice-distal glaciolacustrine deposit. (2) Resting on the upper eroded surface of facies 1 is a 1-1.3m thick bed of horizontally bedded and rippled fine grained light grey (2.5Y 7/1) sand that is rich in zircon (Table 12). This facies probably represents a small delta deposit. (3) An upper rhythmically-bedded silt and clay, 16m thick, that is identical to facies 1 except that it does not grade into a marl. Deposition probably occurred within a distal glaciolacustrine environment by processes of background suspension settling of fines punctuated by small turbidity events.

Table 12. Mean heavy mineral composition (at one standard deviation) of units within the Sheringham Cliffs Formation. Analysis was performed on the 63-125μm fine sand fraction.

	Mundesley Sand Member	**Ivy Farm Laminated Silt Mem**	**Runton Till Member**	**Bacton Green Till Member**	**Trimingham Sand Member**	**Weybourne Town Till Member**	**Runton Sand & Gravel M**
% Opaques	60.9 (3.3)	40.0 (4.6)	41.7 (3.9)	30.0 (3.1)	43.8 (5.9)	40.2 (5.0)	51.5 (3.9)
Non-opaques (% of total non-opaques)							
% Amphibole Group	41.7 (11.0)	20.2 (3.7)	41.1 (3.4)	42.3 (5.2)	33.1 (2.4)	38.0 (8.6)	30.1 (2.1)
% Apatite	2.8 (1.2)	0.5 (0.5)	2.0 (0.4)	1.6 (0.7)	3.3 (0.4)	3.8 (1.8)	1.1 (0.2)
% Epidote	19.2 (5.2)	15.4 (1.4)	22.1 (0.4)	22.8 (4.6)	22.5 (0.5)	18.7 (3.1)	30.3 (2.9)
% Garnet	16.9 (4.4)	41.5 (5.5)	18.4 (1.7)	17.4 (3.5)	25.6 (1.8)	23.3 (7.2)	23.0 (3.8)
% Kyanite	0.7 (0.5)	0.5 (0.1)	0.4 (0.3)	0.4 (0.6)	0.5 (0.3)	0.3 (0.3)	0.4 (0.2)
% Mica	4.8 (3.4)	0.3 (0.6)	2.0 (0.4)	2.2 (1.0)	1.0 (0.6)	1.1 (0.9)	0.5 (0.3)
% Pyroxene	0.6 (1.0)	0.5 (0.9)	2.4 (0.9)	1.9 (1.2)	0.6 (0.2)	1.1 (0.6)	2.6 (0.6)
% Rutile	1.0 (0.8)	1.1 (0.7)	1.0 (0.8)	0.9 (0.4)	0.4 (0.3)	0.9 (0.6)	0.7 (0.3)
% Staurolite	0.1 (0.2)	0.5 (0.3)	0.5 (0.5)	0.5 (0.5)	0.4 (0.4)	0.6 (0.7)	0.8 (0.2)
% Tourmaline	4.5 (1.7)	2.5 (1.8)	3.3 (1.3)	3.8 (1.4)	3.2 (0.8)	2.8 (1.2)	2.5 (0.3)
% Zircon	4.1 (2.0)	16.0 (3.1)	4.9 (1.7)	5.3 (1.3)	8.8 (1.1)	7.9 (2.8)	7.5 (1.1)
% Other	3.7 (1.4)	1.2 (0.7)	1.7 (1.0)	2.0 (0.6)	0.6 (0.2)	1.5 (1.3)	0.6 (0.3)
Number of samples	9	3	5	15	3	11	4

Runton Till Member

The Runton Till Member equates to the diamicton that can be traced along the bottom of the cliffs from East Runton (TG 198428) to Sheringham (TG 169434). Previously, this has been equated to the Third Cromer Till and Contorted Drift (Banham, 1968, 1975) or Laminated Diamicton (Hart & Boulton, 1991b; Roberts & Hart, 2000, 2004). It consists of a dark grey (10YR 4/1) to very dark greyish brown (2.5Y 3/2) matrix-supported diamicton that contains highly attenuated lenses and laminations of sand, chalk (including rafts) and Walcott Till Member material. The matrix calcium carbonate content is low (Table 7). Genetically, it is interpreted as a subglacial deformation till (Hart & Boulton, 1991a,b; Hart & Roberts, 1994; Roberts & Hart, 2000; Lee, 2003). However, detailed examinations of laminae within the till, have led Roberts & Hart (2004) to conclude that prior to subglacial deformation, the primary origin for much of this deposit was subaqueous.

The particle size distribution is broadly similar to the tills of the Happisburgh Formation and the Bacton Green Till Member of the Sheringham Cliffs Formation (Fig. 6). The heavy mineral composition, however, is more like that of the Walcott Till Member of the Lowestoft Formation, supporting the concept that 'Walcott-type' material was being assimilated into the Runton Till (Table 12). Further supporting evidence for this is the derived palynomorph content of the till, which shows an assemblage devoid of associations that can be tied to specific Jurassic and Cretaceous lithologies (Riding, 2001a). The input of fresh materials is demonstrated by the presence of chalk and black flint (20.5%) (Table 5) from local chalk bedrock, and several soft, striated ironstone clasts that are derived from the Lower Cretaceous Speeton Clay Formation and the Jurassic Redcar Mudstone Formation (Riding, 2001a).

Bacton Green Till Member

The Bacton Green Till Member formerly called the Third Cromer Till and Contorted Drift (Banham, 1968, 1975) or Mundesley Diamicton (Lunkka, 1994), is a distinctive diamicton assemblage that can be mapped and identified in coastal sections throughout north Norfolk. From its Bacton Green stratotype (TG 334347), it can be traced westwards via Mundesley (TG 304376) to Trimingham (TG 286386) where it overlies the Mundesley Sand Member. Between Trimingham (TG 281388) and Overstrand (TG 259312) it rests on the Ivy Farm Laminated Silt Member, whereas between East Runton

(TG 197427) and Sheringham (TG 171434) it exhibits a gradational lower contact with the Runton Till Member. Throughout its outcrop it consists of beds of dark yellowish sandy brown (10YR 4/4) to dark grey (5Y 5/1) matrix-supported diamicton (Fig. 6) separated by beds of light grey (2.5Y 8/1) to light yellow (2.5Y 7/4) sand. Many of these sand bodies, which can be traced laterally over several tens of metres, exhibit internal lamination, dropstones, grading and large lens-shaped structures. The till member is interpreted as a subaqueous flow till based on its gradational lower contact with the deltaic Mundesley Sand Member, the lateral continuity of beds, dropstone structures, and variations in texture and sorting. The presence of high-angle reverse and normal faults that cross-cut the deposit, plus intense zones of folding suggest that the deposit was tectonised following deposition.

The Bacton Green Till Member has similar particle size distribution, clast composition (Table 5), matrix calcium carbonate content (Table 7) and heavy mineralogy (Table 12) as the Happisburgh Formation. This supports previous analyses performed by Perrin *et al.* (1979). Derived palynomorphs include associations suggesting input from Whitby Mudstone Formation (Lower Jurassic), Kimmeridge Clay Formation (Upper Jurassic), Lower Spilsby Sandstone / Sandringham Sands (Portlandian) and Speeton Clay Formation (Lower Cretaceous), probably from the area of the Cleveland Basin (Riding, 2001b; Lee, 2003). No diagnostic Scandinavian lithologies were encountered during clast counts, instead the association of Magnesian Limestone, with clasts of Dalradian metasediments, basaltic porphyry, acid porphyry and Old Red Sandstone is typically British (Lee *et al.*, 2002).

Trimingham Clay Member

The Trimingham Clay Member (Trimingham Clay Member of Lunkka, 1994) crops out locally between Trimingham (TG 281388) and Overstrand (TG 259312) where it exhibits a gradational lower contact with the Bacton Green Till Member. It is up to 2.2m thick, and consists of rhythmically-laminated dark grey (5Y 4/1) clays and light grey (2.5Y 4/1) silts which exhibit sharp contacts between couplets and consistent couplet thicknesses. These lithologies represent sedimentation within a distal glaciolacustrine environment where turbidity-current activity was low.

Trimingham Sand Member

The Trimingham Sand Member (Trimingham Sands of Lunkka, 1994) crops out locally between Trimingham (TG 281388) and Overstrand (TG 259312) and occupies small undulations incised into the upper surface of the Trimingham Clay Member. It is less than 30cm thick, and composed of horizontally-bedded and massive sand with occasional ripple structures. On the limited sedimentological evidence available, the Trimingham Sand Member probably represents a small glaciolacustrine delta.

Weybourne Town Till Member

The stratotype of the Weybourne Town Till Member is Weybourne Town Pit (TG 114431) and adjacent coastal sections at Weybourne (TG 114437). It consists of a highly calcareous silt- and chalk-rich matrix-supported diamicton (Fig. 6) that was deposited subglacially by grounded ice (Ehlers *et al.*, 1991; Fish *et al.*, 2000; Lee, 2003; Pawley *et al.*, 2004). The Weybourne Town Till Member corresponds to the 'Cromer Till' variant of the 'Marly Drift' that was defined by Perrin *et al.* (1979) on the basis of its lithological properties, and crops out in the Weybourne-Hanworth-Trimingham area. No stratigraphical association with other 'Marly Drift'-type tills in the Glaven Valley and western Norfolk is made. In the Weybourne area, the diamicton is highly stratified, with highly attenuated and sheared inclusions of Runton Till Member and Bacton Green Till Member material (Lee, 2003; Pawley *et al.*, 2004). Further south and east, in coastal sections to the north of West Runton, Trimingham (TG 269395 & TG 279389) and in trial pits in the Hanworth area (TG 204336), the till is massive and truncates underlying lithofacies without incorporating them (Lee, 2003). The till is distinguished by an abundance of chalk-derived clasts (83.6-92.8%) (Table 5) and high matrix calcium carbonate content (Table 7). Derived palynomorphs and microfossil associations indicate input of materials derived from Toarcian-age Whitby Mudstone Formation (Lower Jurassic), Kimmeridgian-age Kimmeridge Clay Formation (Upper Jurassic), and Santonian-Campanian and Campanian-Maastrichtian zones of the chalk from the present area of the sea floor to the north and northwest (Fish *et al.*, 2000; Riding, 2001a). This supports evidence derived from the measurement of shear plane orientations, fold noses and clast fabrics which indicate a direction of ice flow from the northwest (Banham & Ranson, 1965; Fish *et al.*, 2000; Lee, 2003; Pawley *et al.*, 2004).

Runton Sand and Gravel Member

The Runton Sand and Gravel Member corresponds in part to the Gimingham Sands of Banham (1968) and crops out in the gravitational sag basins between East Runton (TG 198428) and Sheringham (TG 173433) where the deposit rests upon the Bacton Green Till Member, Weybourne Town Member, or a series of un-named localised glaciolacustrine marls. The member is composed of planar cross-bedded, rippled, channelised and horizontally-bedded yellow (2.5Y 7/8) to olive-brown (2.5Y 6/6) sands separated by beds of massive or cross-bedded gravel that were laid down within a proximal glaciofluvial drainage system. The flint content is low (81.8%) compared to other sand and gravel lithofacies. There is a high content of far-travelled erratics (3.7%) including Carboniferous limestone, micaceous schist, quartz-schist, granodiorite, acid porphyry and andesite, typical of a Scottish source (Table 8). No diagnostic Scandinavian lithologies were found.

BRITON'S LANE FORMATION

The stratotype for the Briton's Lane Formation is the Briton's Lane Quarry (TG 168415), Beeston Hill (TG 168434), Sheringham. The formation consists of several coarse-grained outwash lithofacies that truncate and drape pre-existing sediments in the Cromer and Mundesley districts (Table 13; Figs 3, 4, 5). No *in situ* till units have been identified to date, however thrusted slabs of till have been recognised within the Briton's Lane Sand and Gravel Member within the vicinity of Sheringham and Briton's Lane Quarry. Briton's Lane Formation outwash sediments were emplaced prior-to, during and immediately following a major episode of glaciotectonic deformation associated with an ice marginal oscillation into a thick sequence of pre-existing sediments. The glaciotectonic episode formed the push moraine element of the Cromer Ridge. Their relative arrangement is determined by their morpho- and tectono-stratigraphical relationship to one another and the tectonic episode that formed the Cromer Ridge push moraine. The deposits of the Briton's Lane Formation are separated from those of the underlying Sheringham Cliffs Formation by a distinctive unconformity that can be seen within cliff sections at Beeston Hill near Sheringham. At this locality, sands and gravels of the Briton's Lane Formation (Briton's Lane Sand and Gravel Member) form the uppermost stratigraphic unit within the local succession and truncate both the Bacton Green Till Member and the Runton Sand and Gravel Member (Sheringham Cliffs

Table 13. Stratigraphical summary table showing the members of the Briton's Lane Formation. Abbreviations to sources for previous stratigraphical terms: [1]Banham. (1968, 1971), [2]Lunkka (1994), [3]Arthurton *et al.* (1994).

BRITON'S LANE SAND AND GRAVEL MEMBER

Stratotype:	TG 168415 – Briton's Lane Quarry, Beeston Regis
Lithofacies:	Coarse horizontal and massive bedded flint-rich cobble-gravels
Lower contact:	Erosional
Thickness:	Up to 40m in the vicinity of Briton's Lane
Genesis:	Ice-marginal fan complex
Provenance:	Predominantly British with a minor Scandinavian component
Section outcrops:	Briton's Lane Quarry and southwards towards Hanworth, Weybourne Cliffs plus many of the sand and gravel outliers adjacent to the north Norfolk coast including Beeston Hill (Beeston Regis) and Skelding Hill (Sheringham)
Previous stratigraphic terms:	[1]Briton's Lane Sands and Gravels

CORTON WOODS SAND AND GRAVEL MEMBER

Stratotype:	TM 546987 – Corton Woods, Corton
Lithofacies:	Horizontally-bedded flint-rich gravel separated by beds and lenses of sorted pale yellow sand
Lower contact:	Erosional
Thickness:	Up to 6m
Genesis:	Proximal glaciofluvial outwash
Provenance:	British
Section outcrops:	Elevated sand and gravel plateaux areas in the vicinity of Corton (including Corton Woods
Previous stratigraphic terms:	[1]Plateaux Sands and Gravels, [3]Corton Woods Sands and Gravels

BEACON HILL SAND AND GRAVEL MEMBER

Stratotype:	TG 284384 – Gimingham Quarry, Trimingham
Lithofacies:	Shelly cross-bedded and rippled flint-rich sands and gravels; dropsoils and ice-wedge casts and frost cracks are present at Gimingham Quarry; lower horizons exhibit evidence (folding and large thrust faults) of shortening and compressive glaciotectonic deformation
Lower contact:	Erosional
Thickness:	Up to 12m
Genesis:	Proximal glaciofluvial outwash
Provenance:	British
Section outcrops:	Gimingham Quarry, Trimingham and adjacent coastal sections southwards towards Marl Point and Trimingham Beacon
Previous stratigraphic terms:	-

STOW HILL SAND AND GRAVEL MEMBER

Stratotype:	TG 328353 – Paston Cliffs
Lithofacies:	Flint-rich massive gravels separated by thin horizontally-bedded sands
Lower contact:	Erosional contact Sheringham Formation till and outwash deposits
Thickness:	Up to 8m
Genesis:	Proximal glaciofluvial outwash
Provenance:	British
Section outcrops:	Coastal sections between Paston and Sidestrand
Previous stratigraphic terms:	[1]Gimingham Sands, [2]Stow Hill Sands and Gravels

Formation) that occupy the sag-basins (Lee, 2003). This demonstrates the existence of a hiatus between the deposition of the Sheringham Cliffs and Briton's Lane formations, during which the former became consolidated. However, a more complex relationship between the two formations is revealed west of Sheringham (TG 145136 – TG 115437), where the Briton's Lane Sand and Gravel Member locally crops out within a younger set of sag-basins (Pawley *et al.*, 2004). This suggests a polyphase history of sag-basin development in the Weybourne area and confirms the findings of Ehlers *et al.* (1991, fig.143) who recognised 'double sand basins'. The causes of this complexity are not fully understood, but are likely to involve local variations in groundwater conditions. Of critical importance is that the Briton's Lane Formation contains evidence, at least in part, for a Scandinavian provenance (Briton's Lane Sand and Gravel Member).

Stow Hill Sand and Gravel Member

This member corresponds to the Stow Hill Sands and Gravels of Lunkka (1994) and part of the Gimingham Sands of Banham (1968). It rests unconformably on the upper surface of the Bacton Green Till Member between Bacton Green (TG 338345) and Mundesley (TG 319361), and the Weybourne Town Till Member within large tectonically-controlled synclines between Trimingham (TG 279389) and Sidestrand (TG 265397). The member consists of beds of massive, matrix-supported gravel separated by thick beds of horizontally bedded sand which are interpreted as glaciofluvial outwash. A maximum thickness of 8m has been observed in the Trimingham area where the member is in places exposed in tectonically controlled basins. Inland, the unit forms the slightly elevated topography around Paston and the Bacton Gas Terminal. Up to 92% (90.1-92.0%) of the clast content is flint (mainly white, brown and chatter-marked types) with a subsidiary quartzose content (6.4-6.5%), which suggests a major input of material from pre-existing glaciogenic sediments (Table 8). A lithological feature that distinguishes the unit from other sand and gravel lithofacies within the Briton's Lane Formation is the lower amphibole content (18.5% ± 1.9) (Table 14). These sands and gravels were deposited before the widespread glaciotectonic deformation associated with the formation of the Cromer Ridge.

Beacon Hill Sand and Gravel Member

The Beacon Hill Sand and Gravel Member crops out in coastal sections between Marl Point (TG 292383) and Trimingham (TG 283388), and forms the elevated topography between the coast and Gimingham. Its stratotype location is Gimingham Quarry (TG 284384) on the southern outskirts of Trimingham. The lithofacies consists of shelly, cross-bedded and rippled sands with occasional flint-rich (85.7-87.6%) gravel seams. The quartzose content is between 10.3-12.5%, whilst far-travelled exotics are rare (<1%) but ubiquitous in all samples (Table 8). Palaeocurrent measurements indicate a localised direction of flow towards the south and southeast. The sands and gravels were deposited as proximal glaciofluvial outwash within a braided channel. Intraformational horizons of involutions ('drop-soils') and frost-crack features are present within the upper horizons at Gimingham Quarry. Structurally, the lower 5m of the sands and gravels at Gimingham Quarry exhibit steeply inclined bedding (towards the north) with bedding planes that lie parallel to the axial trace within a tight, inclined southwards-verging horizontal fold. These features indicate uniaxial compression and shortening associated with a stress application from the north, whilst the upper 7m of the sands are undeformed. These sands and gravels were therefore deposited during the glaciotectonic episode that formed the Cromer Ridge, with sedimentation continuing following the northwards retreat of the ice margin.

Briton's Lane Sand and Gravel Member

The Briton's Lane Sand and Gravel Member is the thickest (up to 40m) and most spatially extensive member of the Briton's Lane Formation and forms the elevated sections of the Cromer Ridge between the Glaven Valley in the west, the stratotype area of Beeston Regis, and coastal sections between Overstrand and Cromer to the east. The member also forms some of the large sand and gravel outliers between West Runton and Weybourne including Beeston Hill (TG 168434) and Skelding Hill (TG 147135) (Pawley

Table 14. Mean heavy mineral composition (at one standard deviation) of units within the Briton's Lane Formation. Analysis was performed on the 63-125μm fine sand fraction.

	Stow Hill Sand and Gravel Member	**Beacon Hill Sand and Gravel Member**	**Briton's Lane Sand and Gravel Member**	**Corton Woods Sand and Gravel Member**
% Opaques	55.7 (2.5)	52.4 (6.2)	55.1 (13.5)	51.6 (1.8)
Non-opaques (% of total non-opaques)				
% Amphibole Group	18.5 (1.9)	26.2 (9.4)	21.9 (5.8)	22.6 (10.3)
% Apatite	1.6 (0.8)	1.6 (0.8)	1.4 (1.5)	1.3 (1.7)
% Epidote	30.6 (4.1)	23.0 (5.6)	26.6 (8.2)	21.7 (2.7)
% Garnet	11.7 (3.2)	30.9 (7.5)	22.3 (9.5)	11.4 (3.3)
% Kyanite	1.1 (0.6)	0.2 (0.3)	0.9 (0.9)	0.5 (0.4)
% Mica	0.9 (0.5)	0.8 (0.9)	0.3 (0.5)	7.9 (4.3)
% Pyroxene	1.0 (0.5)	2.4 (1.0)	1.9 (0.5)	2.1 (0.5)
% Rutile	2.2 (1.2)	1.5 (0.9)	2.5 (0.6)	3.2 (0.7)
% Staurolite	0.6 (0.5)	0.6 (0.4)	0.9 (0.5)	1.3 (0.4)
% Tourmaline	5.5 (0.9)	2.1 (1.3)	4.1 (2.0)	3.4 (0.8)
% Zircon	15.0 (1.9)	10.3 (5.3)	16.8 (8.1)	24.3 (11.1)
% Other	1.4 (0.7)	0.5 (0.3)	0.3 (0.5)	0.2 (0.3)
Number of samples	7	11	16	3

et al., 2004), and has been traced as far south as the Hanworth area (TG 204336) where it has been recorded in trial pits (Lee, 2003). The sedimentology of the sands and gravels at Briton's Lane Quarry suggests that they accumulated as thick gravel sheets reflecting high-energy sheet-flow deposition. The environment was that of an ice-marginal fan complex that accreted around a pre-existing thrust-stacked ridge of Bacton Green Till Member, with palaeocurrent directions indicating flow between the north and southeast. The lithology is distinctive due to the high flint content (84.5-88.6%) of which the majority is non-chatter-marked (77.7-84.5%), plus the presence of a mixed erratic assemblage comprising clasts of British and Scandinavian provenance (Table 8). Although trace quantities of Scandinavian lithologies were identified within quantitative counts, the majority were found as large cobble-sized erratics. Sedimentary erratics include both Old and New Red Sandstone; metamorphic erratics include quartz schist, graphite schist, micaceous schist and gneiss, migmatite; igneous erratics include rhyolitic tuff, basaltic porphyry, biotite-muscovite granite, andesite, quartz pegmatite, quartz and olivine dolerite, quartz diorite, feldspathic porphyry, rhomb porphyry, acid porphyry and monzo-diorite (Moorlock *et al.*, 2000; Lee, 2003). Of critical importance is the first appearance of metamorphic supracrustals such as gneiss and the high temperature / high pressure migmatites, plus the quartz pegmatites and the rhomb porphyry that are distinctive of southern and central Norway (Lee *et al.*, 2002).

Corton Woods Sand and Gravel Member?

The Corton Woods Sand and Gravel Member corresponds to the Plateau Gravels of Banham (1971) and Pointon (1978), and forms the elevated plateau adjacent to Corton (TM 546987) where thicknesses up to 6m can be observed in coastal sections. The sands and gravels are placed within the Briton's Lane Formation since they exhibit a similar geomorphological relationship to underlying deposits as those in northeast Norfolk. However, a lithostratigraphical link between the Corton Woods Sand and Gravel Member and lithofacies in northeast Norfolk cannot by demonstrated. Its inclusion within the Briton's Lane Formation is, therefore, tentative. Bridge and Hopson (1985) in their study of the Waveney Valley concluded that the Corton Woods Sand and Gravel Member did not relate to the Lowestoft Formation. The lithofacies consist of beds of matrix-supported horizontally-bedded flint-rich (82%) gravel (Table 8) separated by beds and lenses of sorted pale yellow (2.5Y 8/4) sand. A distinctive feature of the heavy mineral composition is the mica non-opaque content (7.9% ± 4.3) which is almost exclusively glauconite, and a high but variable zircon (24.3±11.1) content (Table 14).

CRITICAL STRATIGRAPHICAL ISSUES

As stated previously, the emphasis of this paper is not just to construct a robust stratigraphy for the region, but to use the data underpinning the stratigraphy to test some of the widely-accepted models of the glacial history. Several of these issues are discussed briefly below.

Usage of the term 'North Sea Drift'

The term 'North Sea Drift' has been abandoned as a stratigraphical term since it does not conform to appropriate stratigraphical protocols (Salvador, 1994). Specifically, a stratigraphical qualifier (i.e. North Sea) should not relate to the provenance of the sediment, but should be chosen to represent a critical site or localised area where deposits from this stratigraphical sub-division can be observed (Hamblin *et al.*, 2001). Within the stratigraphical scheme proposed here, all glacial deposits are assigned qualifiers relating to localities and areas where these deposits can be observed in stratigraphical position.

Usage of the terms 'Norwich Brickearth', 'Contorted Drift' and 'Marly Drift'

Usage of 'Norwich Brickearth', 'Contorted Drift' and 'Marly Drift' within the new stratigraphical scheme has also been discontinued. All of these names were originally introduced simply as descriptive terms and then subsequently adopted as formal stratigraphical terms.

The term 'Norwich Brickearth' was originally introduced to define a series of brown sandy diamictons, in places pedogenically modified (Rose *et al.*, 1999b), that crop out throughout the study area and in the adjacent Norwich district (Cox & Nickless, 1972; Perrin *et al.*, 1979). Both the Corton Till and the Bacton Green Till members defined here have previously been assimilated and stratigraphically united under the banner 'Norwich Brickearth'; however, field mapping and sections from the north Norfolk coast demonstrate that these are two distinctive till units separated by the Lowestoft Formation.

The 'Contorted Drift' term was employed by Banham (1975, 1988) to describe a heterogeneous sequence of sediments in north Norfolk that exhibited a complex, polyphase, accretional history. However, it should be noted that this term includes a wide range of deposits in north Norfolk deposited and/or deformed by a variety of mechanisms. The structure of the Bacton Green Till Member is a function of the nature of sedimentary deposition (Lunkka, 1994; Lee, 2003) whereas that of the Runton Till Member is a function of subglacial glaciotectonic deformation (Roberts & Hart, 2000). The complex structure seen in coastal sections at Trimingham, the thickened till sequence within the Britons Lane Quarry borehole, and minor compressional overprints to deposits at other localities, are features caused by ice-marginal thrusting (Hart, 1990).

The term 'Marly Drift' is a term that has been used in relation to the highly chalky diamictons of north Norfolk (Perrin *et al.*, 1979; Ehlers *et al.*, 1987). Within the Cromer district the chalky diamicton corresponds to the Weybourne Town Till Member; however, it is unclear at present how this relates stratigraphically to highly chalky tills within the Glaven Valley and west Norfolk. The possibility that there are several highly chalky tills in northern Norfolk, occurring in different stratigraphical positions and relating to different glacial episodes cannot be discounted.

Scandinavian provenance of the 'North Sea Drift' group of sediments

Analysis of clast lithologies and derived palynomorphs from the tills of the 'North Sea Drift' (i.e. Happisburgh Till Member and Corton Till Member; Walcott Till Member; Runton Till Member and Bacton Green Till Member) demonstrates that they were actually deposited by British ice flowing down the present North Sea coast of England (Lee *et al.*, 2002; Lee, 2003) rather than from Scandinavian ice as previously believed (Bowen *et al.*, 1986; Ehlers & Gibbard, 1991; Lunkka, 1994). Critical evidence includes:

- Absence of diagnostic Scandinavian lithologies such as rhomb porphyry, larvikite and high grade gneisses and high temperature / high pressure supracrustal lithologies (Lee *et al.*, 2002);
- The presence of certain lithologies that are unique to Britain - especially Carboniferous Limestone and coal, Carboniferous palynomorphs; and Magnesian Limestone.

Only the Briton's Lane Sand and Gravel Member, which forms part of the youngest stratigraphical assemblage in the area, shows any evidence of a Scandinavian provenance. The Scandinavian detrital component comprises numerous clasts of rhomb porphyry, high-grade gneisses and various supracrustal lithologies, although these are mixed with more numerous erratics of British provenance (Moorlock *et al.*, 2000). Previously, such occurrences of Scandinavian lithologies, and in particular rhomb porphyry, were found on local beach foreshores (adjacent to outcrops of the Briton's Lane Sand and Gravel Member), or within ploughed fields, rather than as *in situ* occurrences within sections (Moorlock *et al.*, 2001). It is also probable that acid porphyries derived from the Midland Valley of Scotland were misidentified as Scandinavian rhomb porphyry.

Re-definition of the 'Lowestoft Formation'

The redefinition of the 'Lowestoft Formation' presented here essentially follows Bowen (1999), but differs in that the Walcott Till Member (formerly Second Cromer Till or Walcott Diamicton of the North Sea Drift) has been reassigned to the Lowestoft Formation and is stratigraphically equivalent to the Lowestoft Till Member (Table 3).

In previous stratigraphical schemes, the Lowestoft Till and Walcott Till members were considered to have been deposited by co-existing British and Scandinavian Ice Sheets respectively. Absence of Lowestoft Till in northeast Norfolk was explained by the presence of Scandinavian ice (depositing the North Sea Drift) that blocked the eastwards expansion of the British Ice Sheet into the north of the region (Perrin *et al.*, 1979; Bowen *et al.*, 1986; Rose, 1992; Fish & Whiteman, 2001). However, lithological and structural analyses of the tills of northeast Norfolk presented here and elsewhere (Lee, 2003; Lee *et al.*, 2002) demonstrate that these tills are of British provenance, and that the Scandinavian Ice Sheet was not present in the region during deposition of the Lowestoft Till Member.

The reconstruction of the ice flow path that deposited the Lowestoft Till Member (as defined in this paper), agrees with other published evidence (West & Donner, 1956; Perrin *et al.*, 1979; Rose, 1992; Fish & Whiteman, 2001), and demonstrates British ice crossing first the Kimmeridgian (Jurassic) mudstones and then the Chalk in the area of the Fenland Basin before flowing broadly westward over northern East Anglia. Glaciodynamics would also require an additional component of more eastern ice flowing broadly southwards from the Yorkshire Basin into northern Norfolk. A till in northern Norfolk deposited by these ice flow dynamics would contain a mixture of Jurassic and Cretaceous lithologies derived from the Yorkshire Basin (including Whitby and Redcar mudstones, Kimmeridge Clay and Speeton Clay), and Cretaceous Chalk and pre-existing Quaternary sediments derived from the floor of the North Sea and northern Norfolk.

All of the tills in northeast Norfolk were deposited by ice with this flow trajectory, however stratigraphically, the Walcott Till Member is the first available till within the succession that could correlate with the Lowestoft Till Member. This is because the Corton Till Member of the Happisburgh Formation underlies both the Walcott Till and Lowestoft Till members throughout northeast Norfolk and the Waveney Valley. Moreover the Corton Till Member is separated from the Walcott Till and Lowestoft Till members by the lithologically-distinctive Corton Sand Member. The concept that the Lowestoft and Walcott Till members form part of the same till sheet presented here, is further supported by the field mapping, since nowhere are the two tills seen in superposition. In summary, all of the available stratigraphical, mapping, structural and lithological evidence suggests that the Lowestoft Till and Walcott Till members were deposited from a single ice sheet. Thus the compositional differences between the two tills simply reflect different parts of this ice sheet flowing over, and entraining, different outcropping bedrock and superficial lithologies

The Weybourne Town Member (formerly Marly Drift) does not pass laterally into the Lowestoft Till Member (Perrin *et al.*, 1979; Ehlers *et al.*, 1991; Rose, 1992; Fish & Whiteman, 2001). It is instead separated from the Lowestoft Formation by a major disconformity and the Mundesley Sand, Ivy Farm Laminated Silt, Runton Till, Bacton Green Till, Trimingham Sand and Trimingham Clay members of the Sheringham Cliffs Formation (Lee, 2003; Pawley *et al.*, 2004).

Significance of the 'Weybourne Town Till Member'

The significance of the Weybourne Town Till Member is that it represents the first stage during the glacial evolution of northern East Anglia, where pre-existing sediment cover had been removed from the Chalk surface in the present offshore area between Norfolk and Lincolnshire. During this and subsequent ice advances into northern Norfolk, ice sheets were largely flowing over and recycling predominantly chalk with minor quantities of sea-bed sediments. This suggests that a local change in ice flow behaviour might have occurred because of a switch in the subglacial regime (i.e. drainage, rheology etc) from one that is soft-sediment controlled, to one that is locally bedrock dominated.

CONCLUSIONS

The new scheme for the glacial stratigraphy of the Lowestoft, Great Yarmouth, North Walsham and Cromer districts embodies four separate formations, the Happisburgh Formation, Lowestoft Formation, Sheringham Cliffs Formation and Briton's Lane Formation. This terminology is based on detailed scientific evidence, but is sufficiently flexible to enable future stratigraphical discoveries to be incorporated.

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[Manuscript received 12 February 2004; revision accepted 12 July 2004]

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A new stratigraphy for the glacial deposits around Lowestoft, Great Yarmouth, North Walsham and Cromer, East Anglia, UK.

The Geological Society of Norfolk exists to promote the study and understanding of geology in East Anglia, and holds meetings throughout the year. For further details consult our Web Site (http://www.norfolkgeology.co.uk) or write to The Secretary, Geological Society of Norfolk, 32, Lenthall Close, Norwich, NR7 0UU.

Copies of the Bulletin (including older back copies) can be obtained from the editor at the address on p.1; it is issued free to members.

The illustration on the front cover is part of figure 2 from the article by Lee *et al.* in this issue of the Bulletin. It shows the new stratigraphic scheme for the glacial deposits of northeast Norfolk and the Waveney and Yare valleys.

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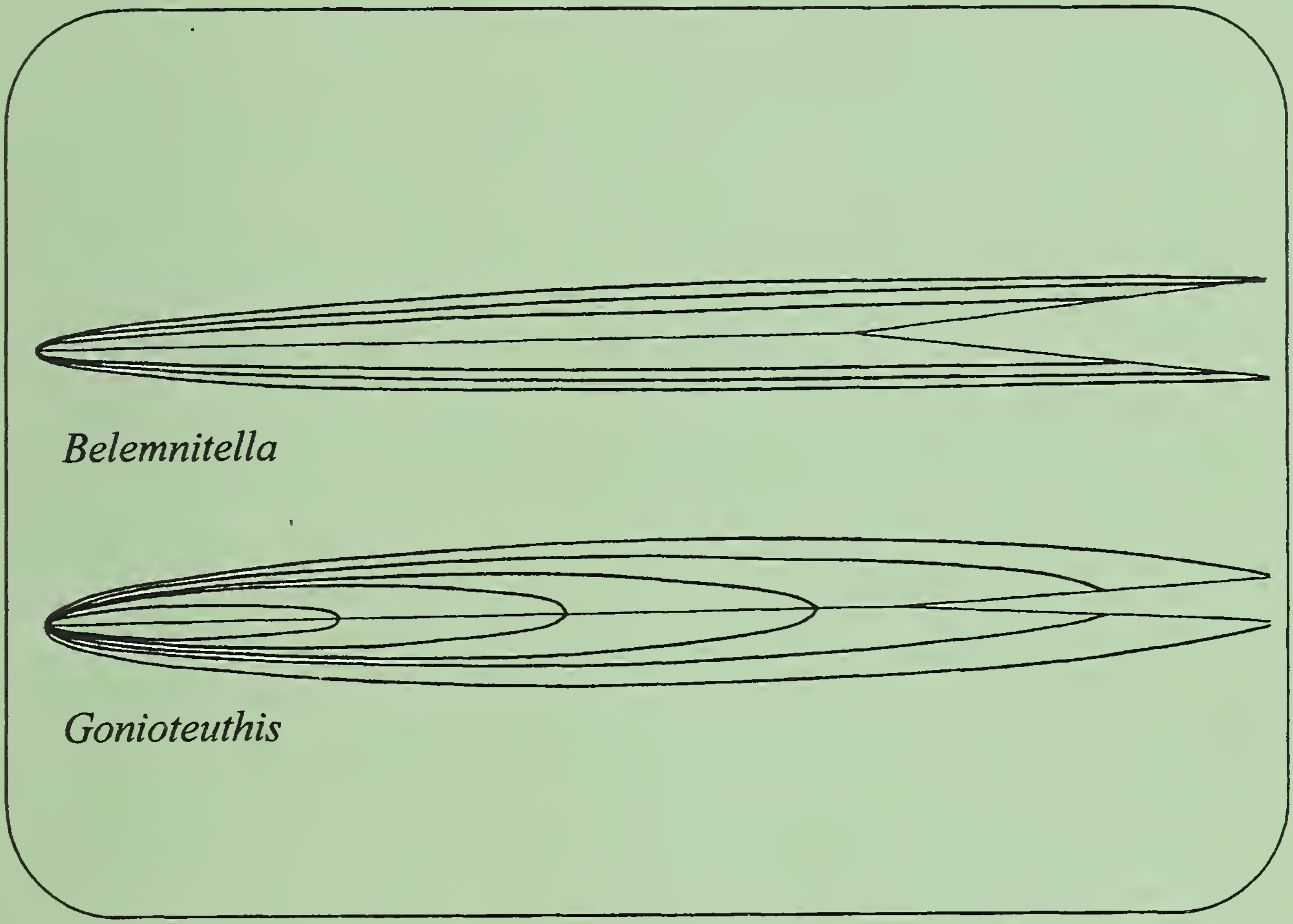

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EDITORIAL

Bulletin No. 54 contains seven papers, five of which concentrate on Norfolk Chalk palaeontology and palaeoecology. Detailed collecting and analysis by Paul Whittlesea of both *in situ* Chalk and flint pebbles derived from it, has turned up a number of interesting finds. Belemnite and bryozoan palaeontology is a strong theme in these papers although rarer discoveries include conifer twigs preserved in flint and bite marks on belemnites made by mosasaurs or other large Chalk sea predators. Of the other two papers, one deals with the topical debate about Scandinavian erratics in East Anglian tills and their first appearance, while the other charts the early history of the Geological Society of Norfolk, based on records found in the rediscovered second minute book of the Paramoudra Club.

At the time of going to press (January 2005) there are a number of papers at an advanced state of readiness and new contributions promised. Bulletin 55 should therefore be ready for publication later in the year. As always, however, I encourage the continued submission of papers on all aspects of East Anglian geology, both from regular and new contributors.

INSTRUCTIONS TO AUTHORS

Contributors should submit manuscripts as word-processor hard copy. We accept typewritten copy and consider legible handwritten material for short articles only. When papers are accepted for publication we will request an electronic version. We can handle most word-processing formats although MS Word is preferred.

It is important that the style of the paper, in terms of overall format, capitalisation, punctuation etc. conforms as strictly as possible to that used in Vol. 53 of the Bulletin. Titles and first order headings should be capitalised, centred and in bold print. Second order headings should be centred, bold and lower case. Text should be 1½ line spaced. All measurements should be given in metric units.

References should be arranged alphabetically in the following style.

BALSON, P.S. & CAMERON, T.T.J. 1985. Quaternary mapping offshore East Anglia. *Modern Geology*, **9**, 221-239.

STEERS, J.A. 1960. Physiography and evolution: the physiography and evolution of Scolt Head Island. In: Steers, J.D. (ed.) *Scolt Head Island* (2nd ed.), 12-66, Heffer, Cambridge.

BLACK, R.M. 1988. *The Elements of Palaeontology*. 2nd Ed., Cambridge University Press, Cambridge. 404pp.

Illustrations should be drawn with thin dense black ink lines. Thick lines, close stipple or patches of solid black or grey should be avoided as these can spread in printing. Original illustrations should, before reproduction, be not more than **175mm by 255mm**. Full use should be made of the first (horizontal) dimension which corresponds to the width of print on the page, but the second (vertical) dimension is an upper limit only. Half tone photographic plates are acceptable when their use is warranted by the subject matter, provided the originals exhibit good contrast.

The editors welcome original research papers, notes, comments, discussion, and review articles relevant to the geology of **East Anglia** as a whole, and do not restrict consideration to articles covering Norfolk alone. All papers are independently refereed by at least one reviewer.

THE FIRST APPEARANCE OF SCANDINAVIAN INDICATORS IN EAST ANGLIA'S GLACIAL RECORD

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ABSTRACT

Lee et al.'s (2004a) claim that Scandinavian indicators do not occur in the earliest (Middle Pleistocene) part of the glacial succession of coastal East Anglia is shown to be mistaken. Norwegian rhomb porphyry clasts may be found with relative ease in the Happisburgh Till Member, the oldest till in the region and, indeed, in the whole of Britain. Lee et al.'s (2004a) failure to discover such material during field and laboratory work is thought to be due to the sparse gravel component of many of the tills, the rarity of Scandinavian rock-types within that gravel fraction and the size distribution of these exotic clasts. Rhomb porphyry erratics may have been introduced afresh into the glacial sequence during the deposition of the Briton's Lane Sand and Gravel Member. The significance of the little-studied East Anglia-wide distribution of Scandinavian material is briefly discussed.

INTRODUCTION

In the face of considerable published evidence to the contrary, members of the British Geological Survey's (BGS) Northern East Anglia Project and their university-based, principally Royal Holloway, University of London (RHUL), collaborators have recently put forward radically new litho- and chronostratigraphic schemes to account for the Middle

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Pleistocene deposits of East Anglia. Long-established views on the provenance, timing and extent of glacial episodes have been challenged in a series of papers from this group (Rose *et al.*, 1999, 2000; Hamblin, 2000; Hamblin *et al.*, 2000; Moorlock *et al.*, 2000a, b, 2001; Lee *et al.*, 2002, 2004a, b; Clark *et al.*, 2004; Moorlock, 2004; Pawley *et al.*, 2004). These proposals have met with some criticism (Banham *et al.*, 2001; Preece, 2001) and this has been partially addressed (Hamblin *et al.*, 2001). Here, we are concerned with the BGS-RHUL claim that Scandinavian indicators do not occur in the earliest East Anglian glacial sediments, an assertion that has been repeated most recently by Lee *et al.* (2004a). We present evidence to show that this view is mistaken.

The lithostratigraphic terms used by Lee *et al.* (2004a) for the Middle Pleistocene sediments of northeast East Anglia are employed throughout this paper (Table 1). Comparisons with earlier stratigraphic nomenclature are provided by Lee *et al.* (2004a).

THE EARLY APPEARANCE OF SCANDINAVIAN INDICATORS IN THE EAST ANGLIAN GLACIAL SUCCESSION

Erratics from Norwegian bedrock sources were first noted in the oldest glacial sediments in East Anglia by Buckland (1823). Some of this exotic material is composed of rhomb porphyry and larvikite, igneous rock-types whose ultimate provenance lies within the Oslo region of southern Norway. Extraordinary care was taken to authenticate the Scandinavian indicators discovered in Britain (e.g. Kendall, 1899). Furthermore, and just as importantly, Buckland (1823) and his successors frequently made it clear that they were referring to erratics that had been found *in situ*. With equally good practice, others have acknowledged that some of the far-travelled clasts they recorded were discovered out-of-context in beaches, at the base of cliffs and on adjacent foreshores (e.g. Hughes, 1894; Kendall, 1905; Harmer, 1910).

The presence of rhomb porphyry, larvikite and other Scandinavian indicators in the earliest East Anglian glacial sediments (the complex commonly referred to as the 'North Sea Drift') has been confirmed by numerous workers (Trimmer, 1851, 1858; Sherborne, 1887; Boswell, 1914, 1916; Harmer, 1928; Solomon, 1932; Bridge & Hopson, 1985; Hopson & Bridge, 1987; Ehlers & Gibbard, 1991; Ehlers *et al.*, 1991).

Table 1. Selected elements of the Middle Pleistocene lithostratigraphy of glacial sediments, northeast East Anglia (after Lee *et al.*, 2004a).

- **Briton's Lane Formation**
    - Briton's Lane Sand and Gravel Member
- **Sheringham Cliffs Formation**
    - Bacton Green Till Member
    - Runton Till Member
- **Lowestoft Formation**
    - Walcott Till Member
    - Lowestoft Till Member
- **Happisburgh Formation**
    - Corton Sand Member
    - Leet Hill Sand and Gravel Member
    - Corton Till Member
    - Happisburgh Till Member

Members of the BGS-RHUL group have stated as recently as 2002 that ice sheets of Scandinavian and northern British provenance deposited tills, sands and gravels in the Cromer district (Moorlock *et al.*, 2002). Hamblin (2000) referred to the presence of rhomb porphyry clasts in the Happisburgh Till Member and of 'Scandinavian erratics' in the 'Hanworth Till Member' (now either the Runton or Bacton Green Till Member). The Happisburgh Till Member is the oldest undisputed till in Britain (Clark *et al.*, 2004). Moorlock *et al.* (2000a, b) drew attention to Gibbard's unpublished discovery of 'large clasts' of rhomb porphyry in the 'Cromer Diamicton', now part of the Sheringham Cliffs Formation of Lee *et al.* (2004a), at West Runton (TG 1843).

SCANDINAVIAN INDICATORS IN EAST ANGLIA: INTRODUCTION DELAYED?

Since 2001, the BGS-RHUL group has more or less consistently denied that rhomb porphyry and other Scandinavian indicators may be found in the Happisburgh and Corton Till Members (e.g. Moorlock *et al.*, 2001, Lee *et al.*, 2002 and Lee cited in Moorlock *et al.*, 2002; but see Moorlock *et al.*, 2002). This belief has been stated most recently by Lee *et al.* (2004a). This startling conclusion was based in considerable measure on the group's failure to discover this material in the course of 'numerous field visits' and 'large pebble counts' (Moorlock *et al.*, 2001; Lee *et al.*, 2002, 2004a).

Lee *et al.* (2002, 2004a) contended that rhomb porphyry erratics first appear in the East Anglian glacial sequence in the Briton's Lane Sand and Gravel Member, an 'ice-marginal fan complex' (Lee *et al.,* 2004a). An unspecified number of rhomb porphyry clasts were collected at the type-site of this unit at Briton's Lane pit, Beeston Regis [TG 168415] (Moorlock *et al.*, 2000b).

180 years of geological reporting rejected

Although BGS-RHUL group members have acknowledged that there are 'numerous published accounts' of rhomb porphyry erratics being found in early East Anglian glacial sediments (Moorlock *et al.,* 2001; Lee cited in Moorlock *et al.*, 2002), there is no evidence that they attempted to evaluate these records. Instead, they concluded that the reports were based on careless observations. They suggested that the indicators may have been eroded from upslope outcrops of the Briton's Lane Sand and Gravel Member and that these became incorporated in slipped masses of till; that some were found at the base of till cliffs; that others were thrown against 'soft' till from beaches during storms; and that acid porphyries from the Midland Valley of Scotland may have been mistaken for those of Scandinavian origin (Moorlock *et al.*, 2001; Lee *et al.*, 2002, 2004a).

SCANDINAVIAN INDICATORS ARE PRESENT IN THE 'NORTH SEA DRIFT'

A striated rhomb porphyry clast measuring ~76 x 53 x 32 mm (Fig. 1) was discovered by us in the Happisburgh Till Member at Happisburgh [TG 387370] after a brief search. The indicator was situated 0.4 m below the top of the unit, and had to be prised out of the till's matrix.

FAILURE TO DISCOVER SCANDINAVIAN INDICATORS

Given the considerable number of records of Scandinavian erratics found in the oldest East Anglian glacial sediments, from Buckland's (1823) original observation to our own recent discovery, Lee *et al.*'s (2002, 2004a) failure to discover rhomb porphyry clasts serves to confirm the rarity of this lithology in these sediments. A number of explanations may be advanced to account for the BGS-RHUL group's fruitless search.

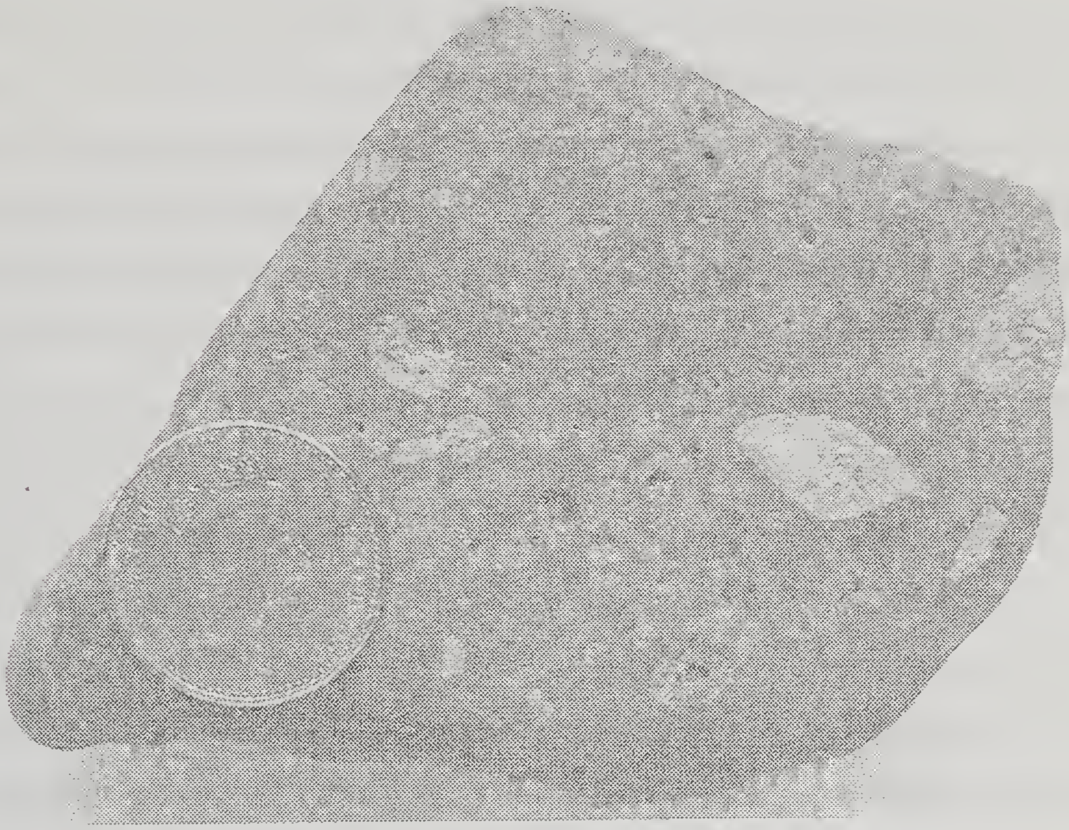

Fig. 1. Striated rhomb porphyry clast, Happisburgh Till Member, found at Happisburgh [TG 387370] on 1 August 2004. The prominent rhombic phenocryst is 14 mm long and 7 mm wide. Photograph by Rhiannon Williams.

Rarity of far-travelled clasts within the sparse gravel fraction of the 'North Sea Drift'

The gravel (>2 mm) fraction of the 'Cromer Till' at Corton is said by Pointon (1978) to be 2.0%, and by Hopson & Bridge (1987) to average 4.6% (of which 4-8 mm = 1.1%, 8-16 mm = 1.5%; $n = 57$ samples). The clast content of the Happisburgh Till Member is typically <1% (Lee *et al.*, 2004a). Approximately 1% of the gravel erratics in the Cromer Tills are 'far-travelled' (Ehlers *et al.*, 1991). Igneous and metamorphic clasts make up 1.3% of the 4-8 mm fraction of 'North Sea Drift till' (Mathers *et al.*, 1987). See also Lee *et al.* (2002). Scandinavian indicators are, therefore, always likely to be elusive in the 'North Sea Drift'.

Examination of an insufficient number of clasts during lithological analysis

The precision with which the actual proportion of rare rock-types can be estimated in clast lithological analyses, even with counts of over 500, is very low. However, the improvement in precision is very small as counts increase beyond 500 (Gale & Hoare, 1991). Since we are concerned not so much with precision as with (apparent) presence or absence of indicators, it is hardly surprising that Lee *et al.* (2002, 2004a) and Moorlock *et al.* (2001) failed to discover rhomb porphyry clasts in their 'stone counts'.

The relative proportions, and indeed the presence and absence, of different lithologies vary with clast size (Boggs, 1969; Gale & Hoare, 1991; Smed, 1993). Given the suspected propensity of rhomb porphyry to occur as relatively large fragments (see below), Lee *et al.*'s (2002, 2004a) examination of the 4-8 and 8-16 mm fractions of the Happisburgh and Corton Till Members may have been inappropriate, but one forced upon them given the necessity to examine a minimum number of clasts, and given the natural size distribution of gravels in the tills. Even if a small rhomb porphyry clast were encountered in the oldest East Anglian tills, it would be difficult to identify with certainty in hand specimen when only part of a large phenocryst was present. The prominent phenocryst in Figure 1 measures 14 mm by 7 mm. Oftedahl's (1957) illustrations of rhomb porphyry bedrock in the Oslo district include one phenocryst measuring 30 x 20 mm, and another >42 x 10 mm. Notwithstanding this potential difficulty, rhomb porphyry erratics have been identified in the 4-8 mm fraction of the 'Norwich Brickearth' (the Corton Till Member of Lee *et al.*, 2004a) at Corton (Bridge & Hopson, 1985). Unspecified 'Scandinavian indicators' also occur within pebbly horizons throughout the 'Corton Sands' sequence (Bridge & Hopson, 1985).

A powerful illustration of size-dependency may be drawn from published results for the Briton's Lane Sand and Gravel Member. Rhomb porphyry clasts were not encountered in lithological analyses of the 8-16 and 16-32 mm fractions (Moorlock *et al.*, 2000b, 2002), although, subsequently, 0.1% of the 8-16 mm fraction was said to consist of Scandinavian erratics (Lee *et al.*, 2004a). Yet 'several large cobbles' of rhomb porphyry were collected at the Briton's Lane pit, Beeston Regis (see above) (Moorlock *et al.*, 2000a, b, 2001, 2002; Lee *et al.*, 2004a). A similar relationship is found in northeast Scotland: large rhomb porphyry clasts may occasionally be seen in outcrops of the Sandford Bay Till Member (Merritt *et al.*, 2003); yet no Scandinavian indicators were found during the examination of the 8-16 mm fraction of the same material.

CONCLUSIONS

Scandinavian indicators have been recorded in East Anglia's earliest glacial deposits by the present authors and by generations of geologists stretching back to Buckland (1823). However, a derived Carboniferous palynomorph association characteristic of the

Westphalian of central Scotland and northern England recovered from the matrices of the Happisburgh and Corton Till Members provides overwhelming evidence of a north British provenance (Lee *et al.*, 2002, 2004a). It is clearly the more abundant gravels and the predominant nature of the matrix of the tills, rather than rare Scandinavian indicators, that throw most light on the origin and movement of the ice and its debris. Nonetheless, the rhomb porphyry erratics denote a Scandinavian influence, of glacial or other character, more or less remote in time, on the Quaternary evolution of the region. But this exotic material does little to illustrate the precise flow directions of the ice sheets as numerous authors have pointed out (Lamplugh in Rastall & Romanes, 1909; Phemister, 1926; Harmer, 1928; Lee *et al.*, 2002).

The rhomb porphyry erratics in the Briton's Lane Sand and Gravel Member may indicate a fresh introduction of this material by ice. It is, however, misleading to describe the provenance of the unit as 'predominantly British with a minor Scandinavian component' (Lee *et al.*, 2004a) as the Scandinavian indicators may have been derived from older sediments.

ONGOING AND FUTURE WORK

An extremely important but neglected question concerns the 'great abundance' (Rastall & Romanes, 1909) of rhomb porphyry and larvikite erratics in till and gravel in Norfolk, Cambridgeshire, Bedfordshire, Hertfordshire, Middlesex and Suffolk (Harker, 1894; Fearnsides, 1904; Rastall, 1904, 1905; Phemister, 1926; Ehlers, 1988; and Ehlers & Gibbard, 1991). Many of these sites are outwith the generally accepted limit of the 'North Sea Drift' outcrop. The widespread distribution of Scandinavian indicators therefore raises issues about the number, extent and timing of British/North Sea Basin ice sheet glaciations of eastern England.

The rhomb porphyry and larvikite clasts appear to have been reworked into Anglian 'Chalky Boulder-Clay' (Rastall & Romanes, 1909) or younger sediments. If the 'North Sea Drift' ice advance had been limited to the present outcrop of the 'North Sea Drift' (it extends inland to Norwich [TG 2308] and to the west of Diss [TM 1180] in Norfolk (Mathers *et al.*, 1987), and to Knettishall [TL 951798] in Suffolk (Lewis *et al.*, 1999)), the Scandinavian indicators could not have been transported to their westerly locations because all subsequent ice movements across this region were directed towards the sector from northeast to south

(Ehlers *et al.*, 1987, 1992; Ehlers & Gibbard, 1991). The exotic material may therefore have been derived from a much more extensive ‘North Sea Drift’ outcrop (Rastall & Romanes, 1909; Ehlers *et al.*, 1991). However, an early significant Scandinavian glaciation (the Fedje Glaciation; Sejrup *et al.*, 2000) that took place ~1.1 Ma ago, may have carried Oslo-district erratics to the North Sea Basin and beyond well before the Happisburgh glaciation.

The geochemistry of rhomb porphyry erratics from inland sites in East Anglia, together with those from coastal outcrops of the Happisburgh Till Member, and from Scottish locations, is to be determined by us (Hoare, Connell, Vinx & Ehlers) in an attempt to establish that their ultimate bedrock provenance lies within the Oslo area.

ACKNOWLEDGEMENTS

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FIRST RECORD OF PHRAGMOCONE AND ALVEOLAR CAVITY OF THE CHALK BELEMNITE *GONIOTEUTHIS*

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ABSTRACT

Two variably complete belemnite guards preserving the alveolar cavity (alveolus) and phragmocone believed to belong to the Chalk belemnite **Gonioteuthis** *Bayle, 1879 were discovered in Chalk-derived flint cobbles collected from glacial sediments at Whitlingham gravel pits, near Norwich, Norfolk. These specimens provide the first data on the alveolus and phragmocone of this belemnite genus and contradict some earlier speculations on their possible composition.*

INTRODUCTION

In recent decades, several very large pits in glacial deposits at Whitlingham in the Yare valley to the east of Norwich have been worked for gravel. Once extraction ceased, the workings, which were very close to the river Yare, were allowed to flood and have become popular recreational lakes or broads. Around the southern perimeter of each broad is a flint pebble beach 1-3m wide. This has provided a rich source of flint preserved Chalk fossils; some of the taxa being extremely rare (Whittlesea 2005a, 2005b). Some of the fossils in these flint pebbles are stratigraphically restricted to rocks of Turonian, or possibly older age, outcrop and subcrop of which is in the west and central part of Norfolk. This implies glacial transport with a westerly component. However, the glacier must subsequently have travelled into the area that is now the Yare valley creating several major and minor Chalk erratics that show easterly overthrusts (Woodward, 1887).

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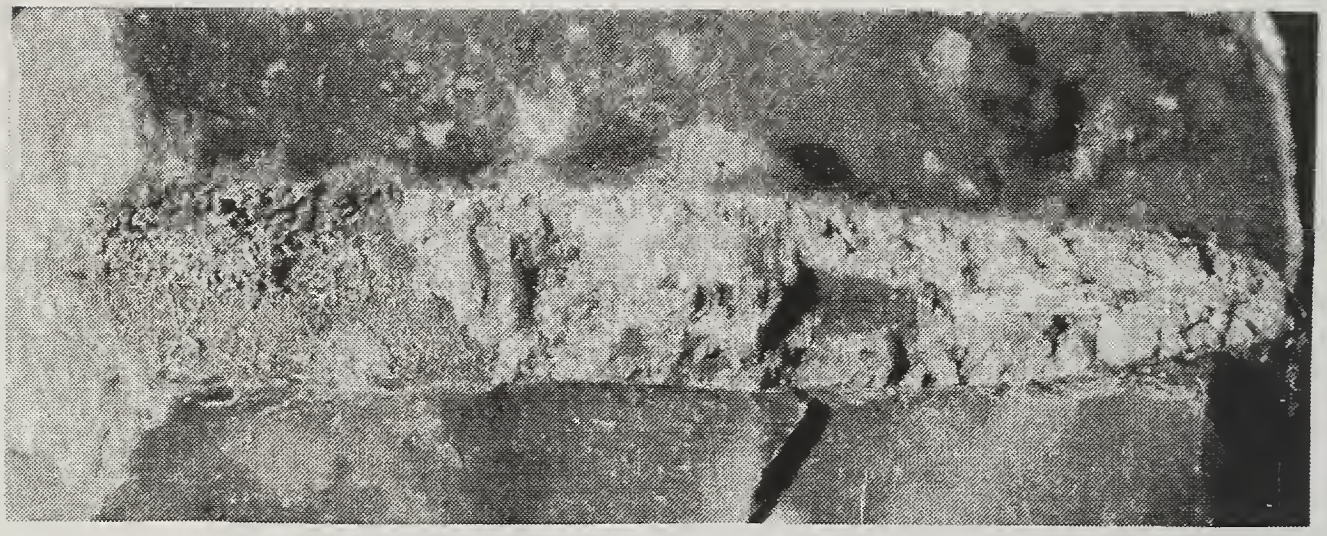

Fig. 1. Photograph of specimen WMP(GB)34/2. The anterior is toward the right. Specimen is 53 mm long.

MATERIAL

The material consists of two belemnite specimens of the genus *Gonioteuthis* Bayle, 1879, enclosed in flint cobbles (Fig. 1). Both specimens are preserved as partial silica replacements of the original calcite guard and/or as external moulds in flint. Traces of either original or diagenetic phosphate are present. One specimen is rather incomplete, but best preserves the phragmocone, excluding that part in the vicinity of the protoconch. The part of the guard hosting the phragmocone shows traces of what may be the boring ichnogenus *Nygmites* within the alveolar wall. None of the guard posterior to the protoconch is present. The second specimen is more complete, but more worn with about 45% of the guard preserved. However, in this specimen it is possible to determine the location of the protoconch and thereby measure the minimum depth of the alveolus containing the phragmocone. Much of the posterior has been dissolved but shows many flint infilled fungal and algal borings attributable to the ichnogenera *Calcideletrix* and *Dendrina*.

DETAILED DESCRIPTIONS

WMP(LB)34/1 (author's collection catalogue number) from the beach surrounding Whitlingham Little Broad [NGR TG 255079].

The fossil is exposed on a broken flint surface 13 mm long by 5 mm wide; within this, the phragmocone is 2 mm wide adorally and 0.6 mm wide adapically. Septa are visible most clearly along a 7 mm interval (Fig. 2) although recrystallisation obscures detail elsewhere and very locally within this interval. 19 septa are clearly present and 25 may be inferred by interpolation. An unusually well-exposed individual septum has a partial length of 0.5 mm, across-which it narrows from 1.1 mm to 1.0 mm. (Damage to the succeeding adoral septum enabled these observations.) The septa are strongly concave

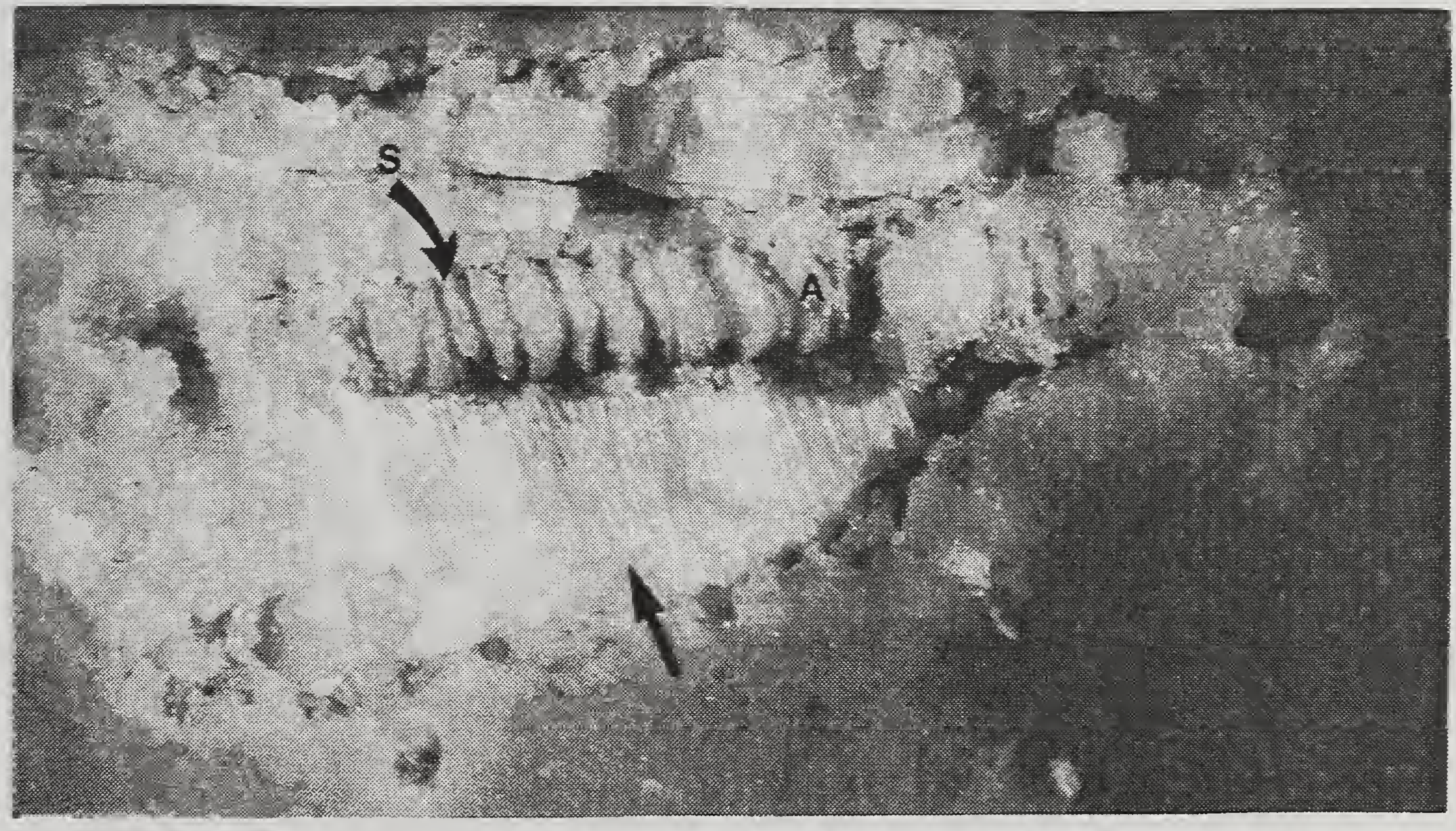

Fig. 2. Photomicrograph of alveolus (A) and septa (S) of WMP(LB)34/1. Growth lines intercept the alveolar wall at 20-25°. Radiating crystallites (arrow) of the guard are clearly visible. The anterior is towards the right. Field of view is 12 mm wide.

adapically (Fig. 2) and are unlikely to have attained a length in excess of ~0.7 mm. No siphuncle components are visible, hence the length separating individual septa along this structure cannot be ascertained. Several relatively well-exposed septa show numerous (~10 >0.5 mm) very-fine, concentric growth-lines. Normally, each septum almost totally encloses the succeeding one leaving just an additional 0.15 mm exposed adapically around the perimeter of each septum. The angle of the phragmocone appears to be very close to 6 degrees.

The composition of the alveolus is clearly a continuation of the guard: it shows radiating crystallites (Fig. 2) traversed by growth lines. Lining the alveolus there is a layer of microcrystalline quartz. Adapically and especially in the vicinity of the inferred position of the protoconch, (not visible in this specimen), the guard contains a boring occupied by a sponge (*Cliona*?) and several sections of gently curving tubular borings (*Nygmites*?) now infilled by silica. In the vicinity of the protoconch some of the radiating crystallites appear to be more densely packed; this could represent either a taphonomic artefact or the possible location of the junction of the alveolus with the pseudo-alveolus. There is no trace of the guard posterior to the protoconch.

WMP(GB)34/2 (author's collection and catalogue number) from the beach surrounding Whitlingham Great Broad [NGR TG 257079].

The specimen occupies an area 53 mm x 8 mm on a broken flint cobble. The phragmocone extends 15 mm into the guard (Fig. 1). The most posterior section of the guard is 17 mm long and largely represented by a flint external mould with silica internal moulds of the boring algae and fungi *Dendrina* and *Calcideletrix* (Fig. 3). About 45% of the guard is present between this section and the alveolar cavity. From the guard that is preserved it is inferred that its overall shape was slender and gently tapering. However, the preserved guard is obliquely and unevenly fractured and thus does not preserve or exhibit most of the central region; the surface is also very worn in places. The relationship between the alveolus to the guard is readily interpreted in this specimen because a substantial section of the latter is preserved. Radial crystallites of silica-replaced calcite form the guard and are traversed by growth lines. Anterior of the protoconch, growth lines, certainly "major" lines (and many finer ones) curve in so as to

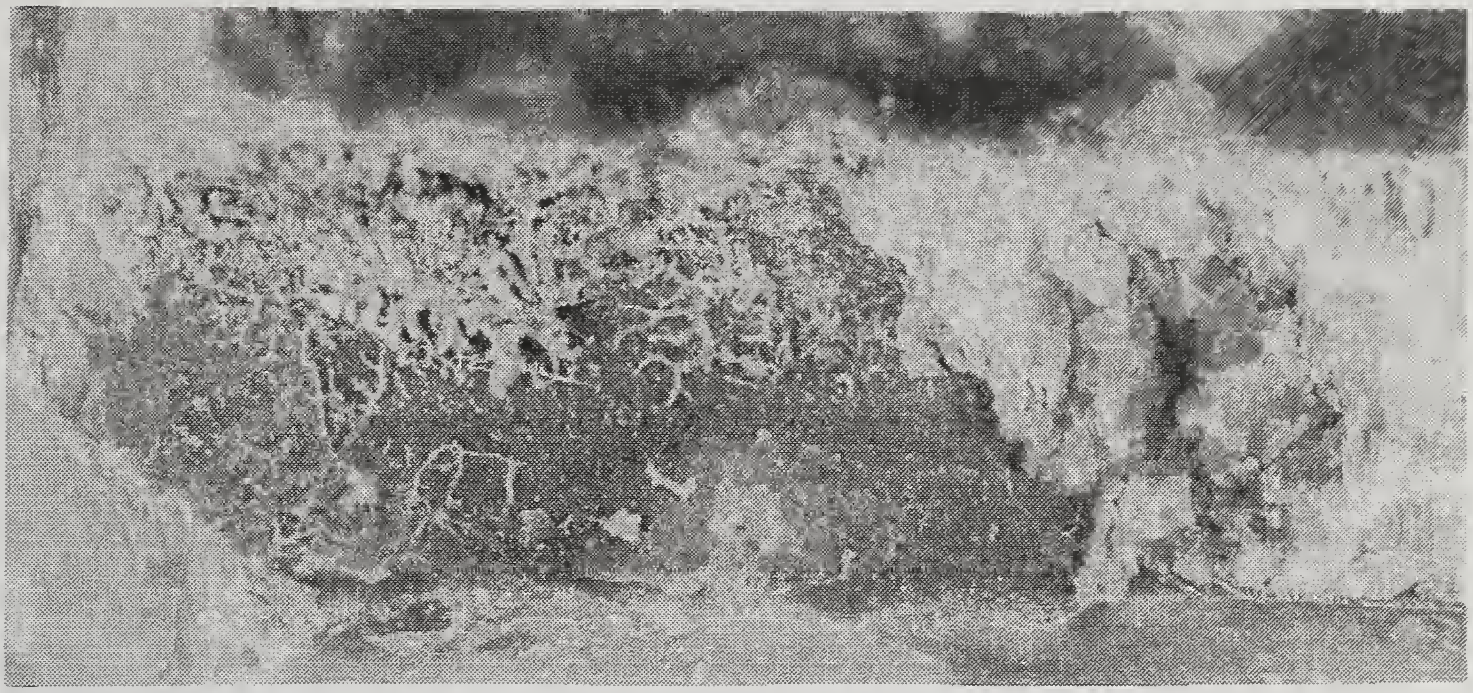

Fig. 3. Posterior of WMP(GB)34/2 showing silica internal moulds of the boring algae and fungi *Dendrina* and *Calcideletrix*. Field of view is 25 mm wide.

intercept the alveolar wall at an angle of 20-25°. Because the ventral fissure cannot be identified with confidence, it is not possible to place the guard in a standard orientation, (i.e. identify the ventral-dorsal plane). The guard is fractured for short lengths along internal growth lines to reveal sections of concave growth surfaces. In the body of the preserved section of the guard, posterior to the protoconch, there are a series of sub-parallel "growth lines" that curve sharply into the centre of the guard (Fig. 4). These are too numerous and consistent to be dismissed simply as taphonomic artefacts. If they are growth lines then they imply that the belemnite did not develop a phragmocone at the anterior end of the guard until late in ontogeny, which is very surprising.

The length of the phragmocone may be seen in its entirety; anteriorly it is largely covered with microcrystalline quartz crystals, but the posterior exposes the protoconch (Fig. 5) and first few septa reasonably well. The protoconch is 0.5 mm in diameter and little more than a shallow concavity 0.2 mm deep, quite unlike the more capacious flask or tulip-shaped protoconch in *Belemnitella*. It is also the only structure in the phragmocone that is convex adapically, although this may be an artefact due to wear. No trace of siphuncle components are discernable.

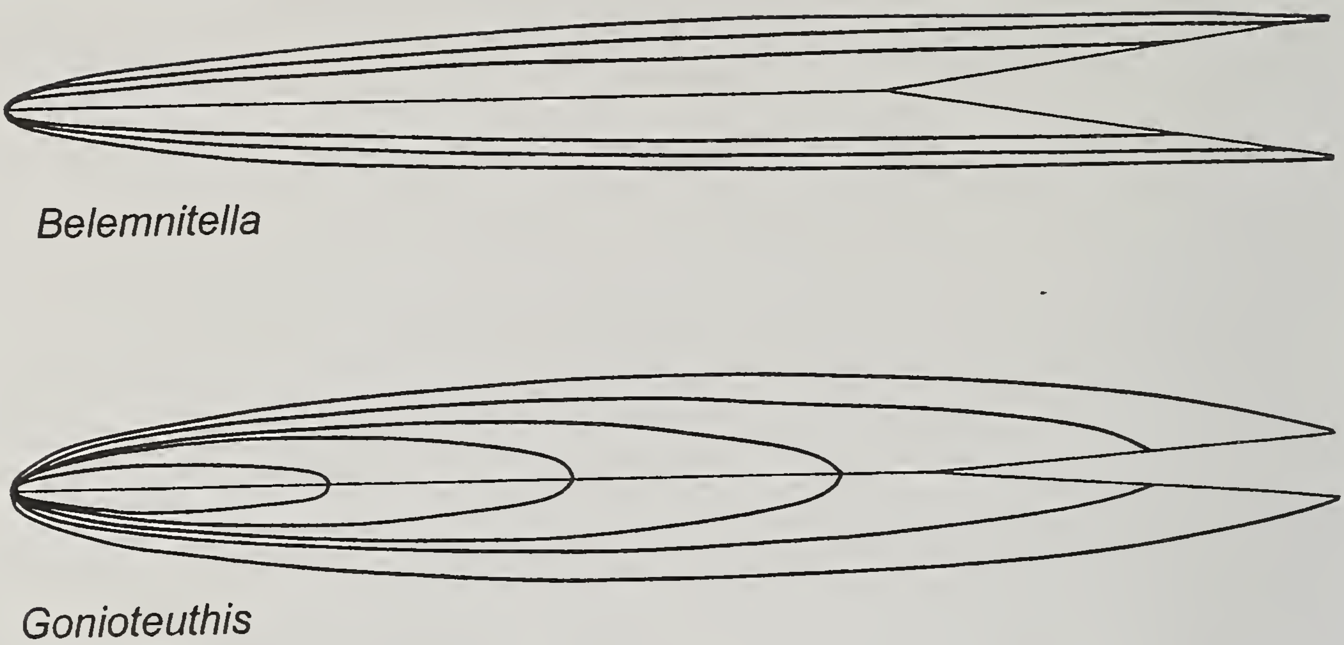

Fig. 4. Illustration of growth lines in belemnite guards. Note how those in *Belemnitella* are concentric about the protoconch, i.e. the base of the alveolus (v-notch), while those in *Gonioteuthis* progressively 'encroach' around the protoconch.

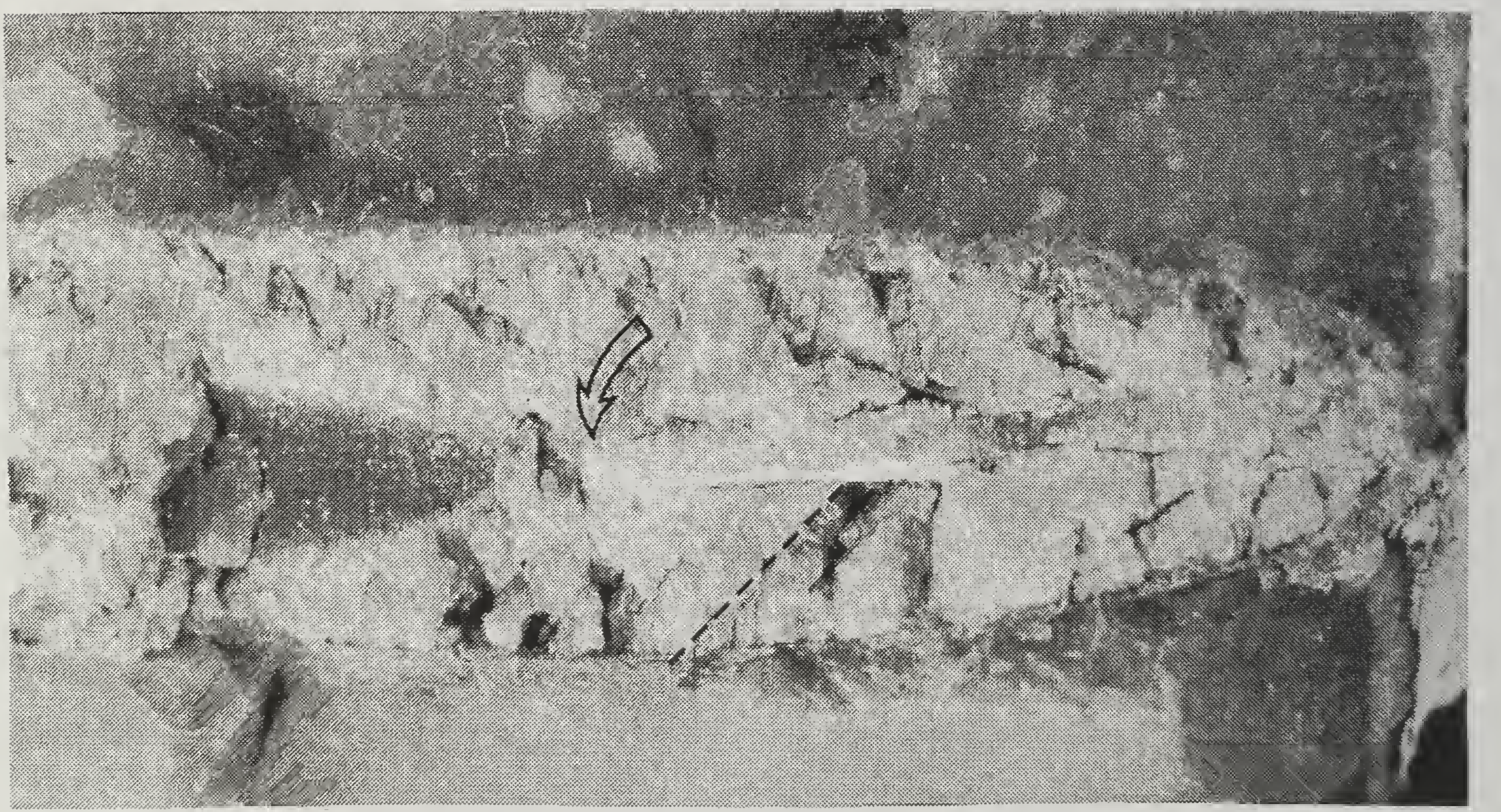

Fig. 5. Detail of alveolus and septa of WMP(GB)34/2. Protoconch (arrow) at the base of the (largely missing) alveolar cavity. Frequent, well spaced, consistently orientated fractures (highlighted by pecked line) in the anterior of the guard meet the phragmocone at a significantly higher angle (60-70°) than the genuine growth lines. Anterior is towards the right. Specimen is 26 mm wide.

DIAGNOSTIC FEATURES OF *GONIOTEUTHIS*

In contrast to younger genera belonging to the family Belemnitellidae Pavlov, 1914 (all of which are differentiated on characters of the guard), the diagnosis of *Gonioteuthis* includes reference to a pseudo-alveolus rather than an alveolus. The pseudo-alveolus is a hollow of variable shape and depth in the anterior end of the guard. It is believed to have been in immediate juxtaposition or otherwise partially enclosed the alveolus proper containing the phragmocone with its septa and siphuncle. It was speculated by Christensen (1975, p. 30) that the alveolus proper might have been organic. The ratio of the depth of the pseudo-alveolus to the length of the guard is a critical factor in species determination and is known as the "Riedel Quotient". However, the horizon from which any specimens are collected must be accurately known and delimited and there must be sufficient of them to undertake a valid statistical analysis. The two incomplete guards described here, collected *ex-situ* in a glacial deposit do not satisfy either of these criteria. *Gonioteuthis* guards may show a short ventral fissure and traces of vascular impressions but again, these cannot be detected in these specimens.

The material described here shows the guard extended sufficiently anterior of the pseudo-alveolus to produce an actual alveolus that housed a deep, narrow phragmocone. It consisted of radiating calcite crystals otherwise identical to the main body of the guard and certainly shows clear traces of growth lines. The specimens figured by Christensen (1975) had been split ventro-dorsally and exhibited the "bottom of the ventral fissure" and the "splitting surface" in the anterior end of the guard occupied by the pseudo-alveolus; two taxonomically important features. A random plane of fissure might well have missed these features, so their absence in the material described here is not crucial. A Riedel Quotient is only valid if a "separation point" exists between the alveolus and pseudo-alveolus at a constant position (statistically significant) within a population at a given stratigraphic horizon. It is of some concern that no trace of such a junction with or between the pseudo-alveolus and alveolus could be seen.

Comparing details of the phragmocone of *Gonioteuthis* with *Belemnitella* cf. *langei* Jeletzky, as described by Whittlesea (1991), the alveolar angle is much smaller (6 degrees versus 19 degrees) and the septa very crowded. Their more even spacing is probably a consequence of the small alveolar angle. Indeed, the septa are so closely overlapping (in "cone-in-cone" fashion) that it was only possible to see the details reported above because some septa were damaged, allowing a view of more axial areas. In *Gonioteuthis*, septa are thick, relatively evenly spaced, and are concave posteriorly.

By contrast, *Belemnitella* septa are very much thinner, rapidly increase in spacing as the phragmocone widens and are convex posteriorly; it is also possible to get a good view of the siphuncle and its components. (The author has collected many more specimens since that described in Whittlesea, 1991).

ACKNOWLEDGEMENTS

I thank Stephen Bennett for help preparing one specimen and help with operating the scanning electron microscope (SEM) in the School of Environmental Sciences, University of East Anglia. The Head of the School of Environmental Sciences kindly gave permission to use the SEM.

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GLOSSARY

Adapical: towards the apex (posterior) of the guard and the rear of the animal.

Adoral: towards the oral (mouth, anterior) end of the animal (front, head, tentacles, etc.).

Alveolus: (synonym: **alveolar cavity**): the conical cavity in the adoral end of the guard that houses the conical chambered phragmocone.

Ontogeny: the series of stages that an organism passes through during life, often associated with significant changes in size or shape, and / or the acquisition or loss of organs.

Phragmocone: the conical chambered shell of the belemnite animal, analogous to the shell of an ammonite.

Protoconch: the initial shell of the belemnite animal located at the base of the phragmocone.

Septum (plural: **septa**): one of the curved walls of the phragmocone that partition it into separate chambers.

Siphuncle: a tube, located on the ventral interior margin of the phragmocone, passing adorally from just in front of the protoconch through each successive septum as it forms.

Ventral fissure: a fissure or slit that commences on the interior of the alveolus a short distance from the protoconch before connecting with the exterior of the ventral surface of the guard. It continues adapically from that point.

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In addition, the society published a special Jubilee volume (edited by Roger Dixon) to commemorate its 50th anniversary. This volume is dedicated to Prof. Brian Funnell and contains a number of articles about Prof. Funnell, his research and the early days of the Society. The Jubilee Volume is free to GSN members. The remainder will be sold at cost (£8-50). Sales will be made on a first come first served basis.

If you would like to place an order please discuss your requirements with Julian Andrews at UEA, preferably on the following e-mail address: j.andrews@uea.ac.uk

Or by post to: Dr Julian Andrews, School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ.

EVIDENCE FOR LOWER MAASTRICHTIAN BRYOZOAN PACKSTONES AND WACKESTONES IN THE NORFOLK CHALK

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INTRODUCTION AND MATERIAL

Chalk-derived, rounded flint and chert pebbles and cobbles containing silicified or partially silicified fossils and matrix of a former bryozoan limestone, have recently been collected from the north Norfolk coast between Sheringham [NGR TG 159 445] and Cromer [NGR TG 219 424] and from the southern shore of recently closed gravel pits at Whitlingham [NGR TG 257079], 2 km ESE of Norwich. The pebbles and cobbles are typically of oblate-irregular shape (<10 cm across), usually with a distinctive grey or white core and yellow, orange, ruddy or brown cortex (usually the latter). Almost pure white angular chert pebbles are much less common. While not rare at these two localities the fossiliferous pebbles constitute <0.01% of the clasts present.

In some specimens both the former limestone matrix and fossils have been silicified. In other specimens just the matrix is silicified while former calcitic or aragonitic skeletal elements have been partially or completely dissolved leaving voids or moulds. Favourably orientated, unworn external moulds of fossils can be cast using modelling clay or silicone rubber to enable species level identification, although in many cases it is not possible to identify them below family taxonomic level.

FABRIC AND PRESERVATION

The flints preserve two chalk fabrics; (1) where constituent grains touch and support each other, but where the intergrain space is mud-filled (packstone texture (Fig. 1) of Dunham, 1962); and (2), lime mudstones with >10% grains, where grains are matrix supported (wackestone texture of Dunham, 1962). Fossil preservation is generally very good to excellent with little evidence of wear; both brachiopod and bivalve shells retain

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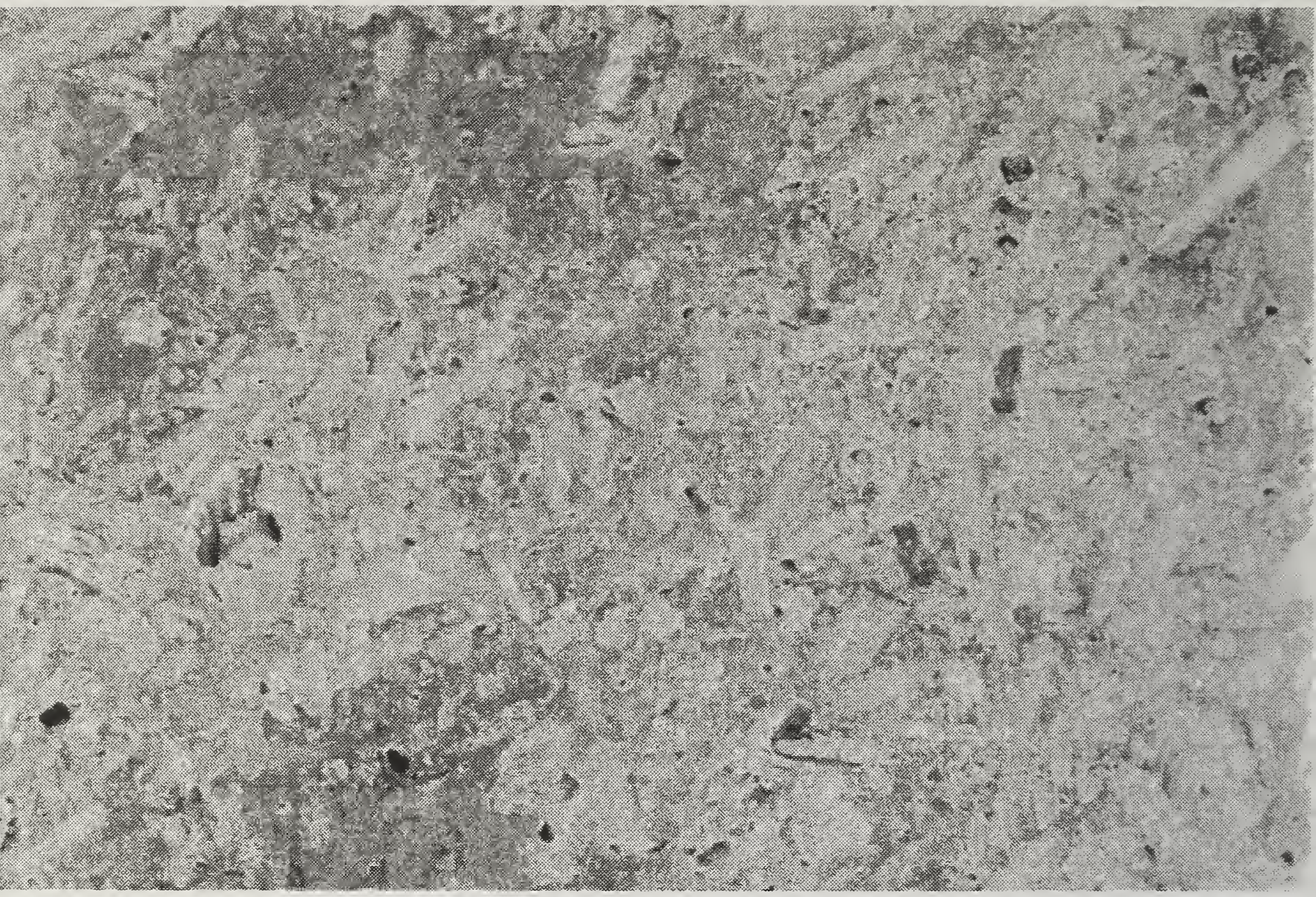

Fig.1. Packstone fabric in flint showing mostly vinculariform bryozoa fragments: view of sawn face of specimen WMP(GB:B1) in authors collection. Field of view is 22 mm wide. Whitlingham Great Broad.

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ornament and are usually articulated. Most of the major marine phyla are represented including algae, (calcispheres, dasycladacean algae, possible sea-grasses), foraminifera, sponges, brachiopods, bivalves, regular and irregular echinoids, asteroids, comatulids, serpulids, bryozoa and fish (Table 1). There is, however, an extraordinary abundance of bryozoa colonies (Fig. 1; >90% by volume in some samples). Of these, cyclostome bryozoa (order: cyclostomata) constitute about 60-70% of the total number of colonies, while cheilostomes (order: cheilostomata) constitute about 90% of the diversity and include some encrusting taxa that form very much larger colonies than the cyclostomes. Most of the bryozoan colony fragments are of branching vinculariform or erect bilaminar types (terms defined in Whittlesea *et al.*, 2005; this volume) and many of these are much less fragmented than in normal Chalk specimens. Differential black staining (by ?manganese dioxide) of fracture surfaces has often enhanced the contrast between matrix

Table 1 List of taxa identified to date

Algae: *Thalassocharis?*, Dasycladaceans?.

Brachiopoda: *Carneithyris carnea* (Sowerby), *Aemula* sp., *Argyrotheca* sp., *Terebratulina chrysalis* (Schlötheim), *Magas chitoniformis* (Schlötheim), *Kingena pentangulata* (Woodward), *Kingenella* sp.

Bivalvia: *Aequipecten* sp., *Inoceramus* sp.

Echinodermata: '*Cidaris*' sp., *Salenia* sp., *Echinocorys* sp.

Asterozoa: *Metopaster parkinsoni* (Forbes).

Comatulida: *Applinocrinus cretaceus* (Bather)

Bryozoa: *Pustulopora* spp., '*Membranipora*' spp., *Micropora* spp., Aechmella spp., *Hoplitaechmella vespertilio* (von Hag.), *Onychocella inelegans* (Lonsdale), *Onychocella* spp, *Puncturiella* sp. nov.?, *Anornithopora* sp., *Leptocheilopora 'magna'* Lang, *Castanopora magnifica* (d'Orb.), *Ubaghsia crassa* Lang, '*Porina*' spp., '*Vincularia' foricula* Brydone.

and clasts in the wackestones, presumably because the fine-grained matrix readily absorbed pigment leaving bryozoan and other clasts a brown /white colour.

PALAEOENVIRONMENTAL INTERPRETATION

Presence of photosynthetic organisms (algae) indicate deposition in shallow water within the photic zone, while good preservation of delicate organism's (bryozoans) and the presence of fine grained matrix suggests deposition in low energy environments. The fabrics resemble those from bryozoan bioherms from Stevns Klint (Denmark, e.g. see Berthelsen, 1962) and the presence of algae re-calls bryozoa-algal associations described by Voigt, (1981). Voigt suggested that phytal substrata and preponderance of rigid erect zoarial forms indicate water depths in the range 30-50m.

AGE

The presence of the bryozoan *Vincularia foricula* Brydone found in a few samples suggests a Lower Maastrichtian age. First appearance of this bryozoan in the Norfolk

Chalk is in the Lower Maastrichtian at Trimingham (Brydone, 1930, p. 45), although Brydone seems not to have discovered *in situ* material of this distinctive Chalk facies. These distinctive flint pebble lithologies cannot be matched with known flint or chert horizons from the Norfolk Chalk.

Observations by the author eliminate the Lower Maastrichtian at Sidestrand as a possible source of these cherts; similarly the Beeston Chalk and most of the Paramoudra Chalk are now sufficiently well known that current and historical exposures can be eliminated as a possible source. Many of the bryozoa from these pebbles, including those not yet formally identified, are unknown from pre-Maastrichtian or Maastrichtian samples the author has examined.

FUTHER WORK

Definitive identification of the algal sea-grasses is clearly important and material has been forwarded to a palaeobotanist. Further taxonomic research is scheduled for the material already collected and this should clarify issues regarding bryozoa diversity, and the possibility that multiple, geographically restricted areas of bryozoan limestone facies existed in the Norfolk Chalk.

ACKNOWLEDGEMENTS

Thanks are due to Norman Peake and Dr. Paul Taylor for advice and comment, Dr. Eckart Håkansson for leading a field trip to Stevns Klint, Denmark and to Dr. Raymond van der Hamm for comment and advice on marine paleobotany.

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UPPER CRETACEOUS CONIFER TWIG PRESERVED IN FLINT FROM WHITLINGHAM GREAT BROAD, NORWICH

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INTRODUCTION

A flint pebble collected from a beach of glacially-derived gravels at Whitlingham Great Broad, near Norwich (NGR TG 255079) contains a distinctive blue-white opalescent fossil. Initially, it was thought the fossil was a fragment of fish skeleton, as fish scales, teeth and bones are known to occur in these types of flints. However, examination with a binocular microscope revealed clearly the grain of wood together with alternating leaf insertion scars (Fig. 1). Scanning electron microscopy (SEM) further revealed the presence of possible parenchymal cells, i.e. thin-walled cells of variable size and form. SEM examination of a modern larch twig, first with the bark removed to reveal the outer surface, and then of the inside of the bark from the same twig provided reference images. Comparison with the modern larch twig confirms that the flint fossil represents the inside of the woody part of a twig immediately below its junction with the bark. The individual leaf scars are 1.75 – 2.00 mm long and 0.55 – 0.8 mm wide.

Carson (1991, p. 477) when commenting on a model for the silicification of wood proposed by Leo & Barghoorn (1976) noted that original organic substrates are used as a template onto which opaline silica accumulates. This would infill any cell voids, an observation borne out by SEM examination of this specimen.

IDENTIFICATION

Dr Peter Murphy made the following observations on the specimen: "Wood species identification is generally based on examinations of sections in transverse, radial longitudinal and tangential longitudinal directions, (Schweingruber 1982; Hather 2000). This specimen of mineral-replaced twiggy wood is too thin (4 mm x 12 mm) for sections to be discernable. All that can be examined is the exposed surface. This appears to

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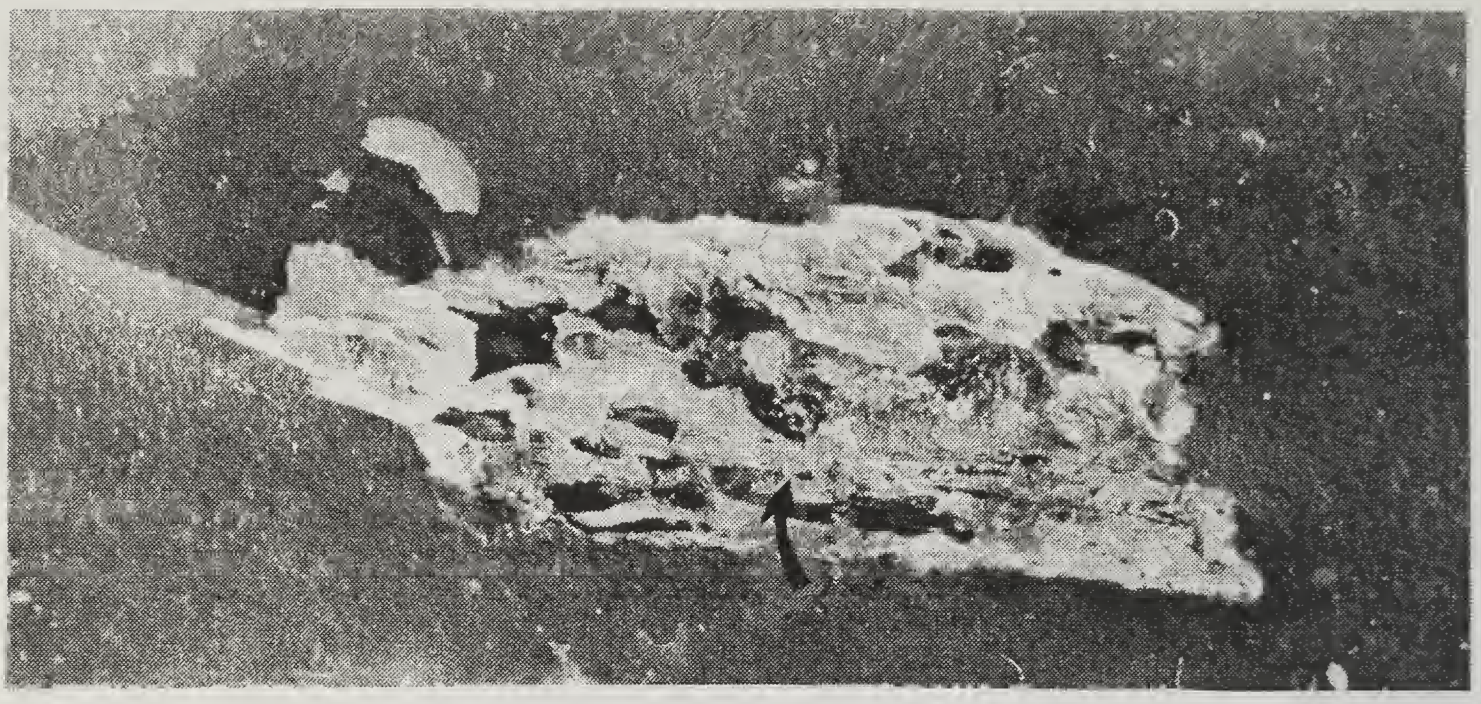

Fig. 1. Photograph of the flint preserved twig fragment showing leaf-scars (arrow). Fragment is 11 mm long.

represent the surface after loss of bark. Features that appear to be leaf insertion scars survive, and the specimen has an overall longitudinally-striated structure, representing coarsely-replaced fibre and tracheid cells. That it *is* wood there is little doubt, but identification to genus or species is not possible."

PROVENANCE

Comparison of this specimen with other flints of similar coloration and cortex that included stratigraphically useful fossils (e.g. *Gonioteuthis* guards Whittlesea, 2005) suggest a possible Lower Campanian age. The presence of wood in Upper Cretaceous marine sediments suggests an origin as driftwood that became waterlogged and sank.

ACKNOWLEDGEMENTS

I am deeply grateful to Peter Murphy for confirming the identification of the sample and to Lafarge Aggregates for access to Whitlingham Great Broad. I thank Stephen Bennett for help with the scanning electron microscope (SEM) in the School of Environmental Sciences, University of East Anglia. The Head of the School of Environmental Sciences kindly gave permission to use the SEM.

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PATHOLOGICAL BELEMNITE GUARDS FROM THE UPPERMOST CAMPANIAN CHALK OF NORFOLK

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ABSTRACT

Although pathological belemnites are rare in the uppermost Campanian Chalk of Norfolk they are described here from two localities near Norwich. The commonest pathology is interpreted as a congenital growth defect and provides insight into tissue growth and repair mechanisms. A scarcer pathology is attributed to non-fatal predation, rare examples of which enable estimates to be made of the thickness of tissue enveloping the guard. These pathologies also inform debate on possible feeding strategies used by some belemnite predators. Evidence of intra-specific interactions is also discussed.

INTRODUCTION

This paper is based on observations and data from 24 belemnite guards with a variety of pathologies, i.e. deformities caused by disease or injury. The specimens were collected from two horizons in the uppermost Campanian Chalk of Norfolk and comprise <0.1% of the fossil population. The first horizon is a hardground complex at the top of the Pre-Weybourne-5 Chalk; this cropped out below the water table in the base of the now infilled chalk pit at Keswick near Norwich, (NGR TG 212048; Pitchford 1990). The second horizon is in transgressive facies of the Beeston-3 Chalk currently exposed at the top of Caistor St. Edmund chalk pit, (NGR TG 238046; Wood 1988; Pitchford 1990; Christensen 1995). The specimens have not been identified to species level because they are either incomplete or the pathologies interfere with the critical measurements used to assign species.

Pathological guards probably result from failure of tissues enveloping the guard to grow normally, or from non-fatal attacks by predators, (e.g. mosasaurs, sharks, fish) damaging tissues and other structures.

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GUARD FEATURES

The structure of fossil coleoidea – including members of the Order Belemnitida Zittel 1895 – are discussed in detail by Jeletzky (1966, p. 107-152). Belemnite guards consist of calcite crystals originating in an apical generative zone initially located adapical to the primordial guard, itself immediately adapical to the protoconch (see glossary for definition of unfamiliar terms). The apical generative zone produced multiple clusters of tiny, evenly-sized and crowded loci, from which spherical clusters of calcite crystals radiate (Fig. 1). Contact between crystals emanating from adjacent loci terminated growth in some crystals from each. The guard grew between the adapically migrating apical generative zone and a layer of enveloping tissue. The enveloping tissue increased the guard's diameter by extending those calcite crystals that survived contact termination. It produced alternating thicker calcitic layers (~0.1 mm thick at DVDP) and thinner organic layers (<0.01 mm thick at DVDP) as it did so. Normal, controlled growth

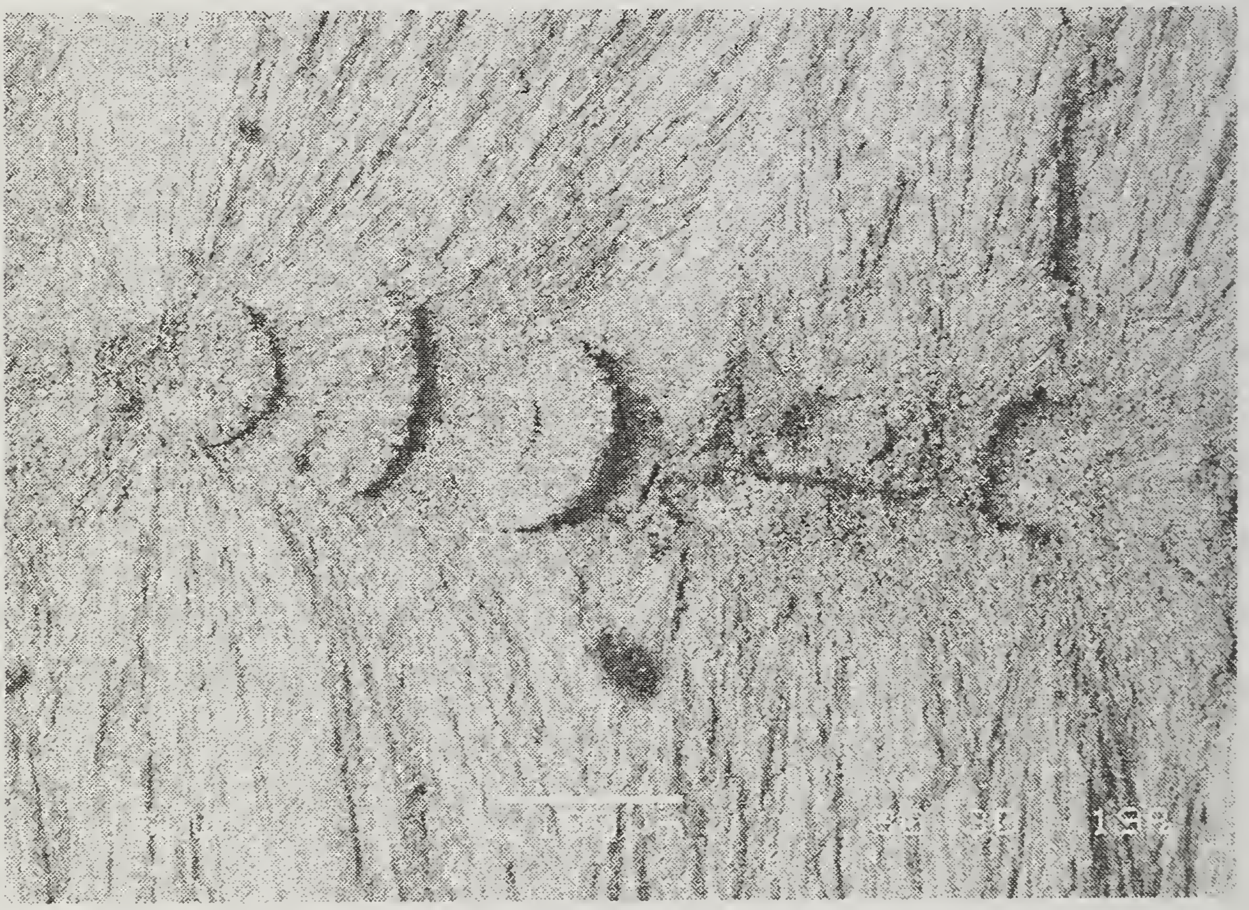

Fig. 1. Scanning electron microscope image of radiating spherules of calcite generated in the apical generative zone. White scale bar is 100 μm long. Note how contact between crystallites from adjacent spherules terminates further growth in each. Author's catalogue number WR(ER/2).

produced closely packed, radiating sets of calcite crystals terminating at each growth increment in a smooth guard surface.

Tangential sections through a guard show early growth rings to be crenulate; these become progressively more evenly convex as subsequent growth rings were added. This is a consequence of the progressive reduction in the number of loci contributing crystals to later growth rings in a set fraction of guard circumference. It also emphasises that the discrete calcitic layers are not completely isolated from each other by the intervening organic layers.

Belemnitella guards usually exhibit clear signs of vascular imprints on their exterior. A vascular system would have been essential for supplying layers of tissue with metabolites needed to secrete outer layers of the guard and to lateral fin muscle tissue.

SCAR TISSUE

"Scar tissue" is defined here as areas of the guard surface where the normally closely packed calcite crystals have become to a greater or lesser extent isolated from their neighbours. As a result, the scar tissue appears much paler than surrounding areas as the crystals admit light not just through their terminations but also from their sides. In some instances the tips of these crystals may swell greatly to plug what was probably an abscess (Fig. 2). The scars typically grew in alignment with the guard axis and are generally commoner on the ventral surface. Scar tissue may have been initiated at any stage of guard growth and may subsequently have been overgrown by normal tissue. In such cases, the only indication of the former presence of a layer or area of scar tissue may be localised gross asymmetry in the guard.

CONGENITAL PATHOLOGIES

The commonest pathology consists of generally ventrally located, axially aligned, variably elongated and depressed grooves and/or elliptical embayments that may be associated with scar tissue. The degree of elongation may be very slight, producing little more than a minor depression in the surface of the guard, or extend as one or more lines along the surface, sometimes migrating onto one or both of the lateral sides.

In some specimens the putative ventral slit has clearly opened and sealed repeatedly, producing elliptical embayments connected by grooves, although these are not always associated with scar tissue. In one otherwise normal specimen, scar tissue is

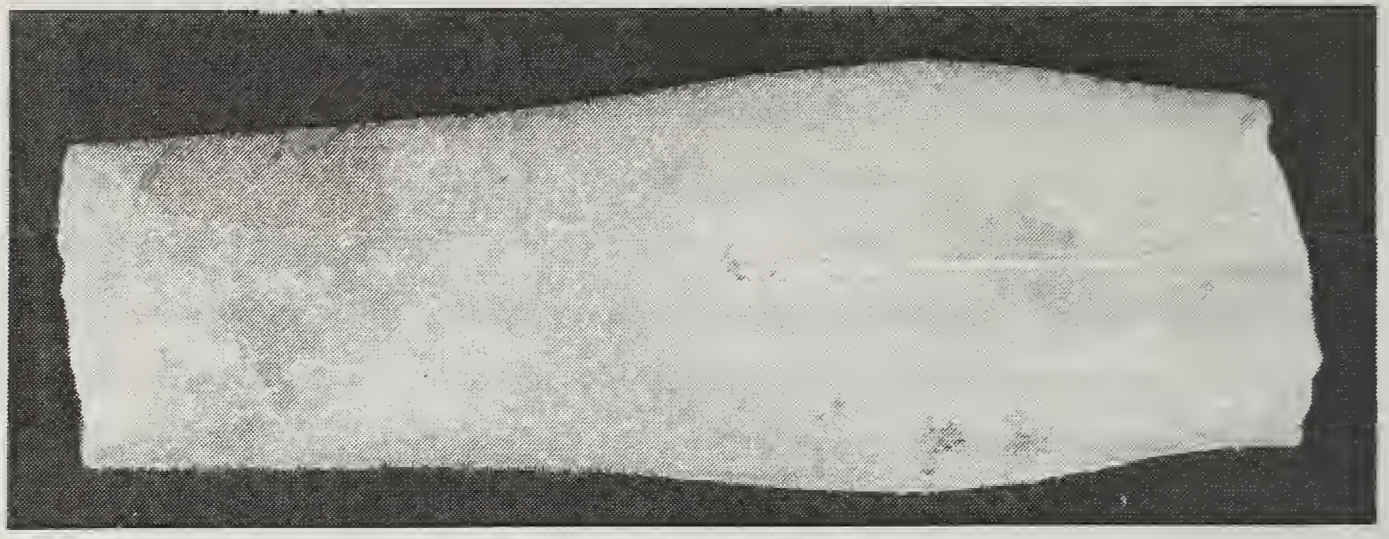

Fig. 2. Grossly distorted, adoral end, of a broken guard seen in dorsal view. The area is centred on the alveolus and a copious amount of scar tissue is present on all surfaces. Specimen is 3.5 cm long. Author's catalogue number CSE(S3)20/2.

confined to the dorsal-lateral furrows and a small region on the ventral surface of the guard immediately beneath its apex. Two specimens of the bivalve *Gyropleura* encrust the guard, in places overlapping the scar tissue that is clearly visible beneath them proving that the scar tissue is an original feature of the guard (i.e. not diagenetic alteration). As no plausible candidate sites for wounds have been identified on the guard the pathology is inferred to be congenital.

Many of these slit-like openings associated with scar tissue were initially interpreted as failed predation attempts. However, the front teeth of a predator attacking from the rear would have produced symmetrical slit-like wounds perpendicular to the axis of the guard on opposing dorsal and ventral surfaces. As this configuration of slits is not seen it suggests the slits resulted from congenital failure of the tissue envelope to fuse completely.

PREDATOR INJURIES

Damage to the guard apex may have terminated or severely retarded elongation of the guard whilst the outer layer continued to add calcite to its surface, resulting in a severely deformed guard (Fig. 3). In this specimen it is not clear whether the deformation was caused by injury to the apex or whether it was another congenital deformity. However, clear predator injuries are known (Fig. 4).

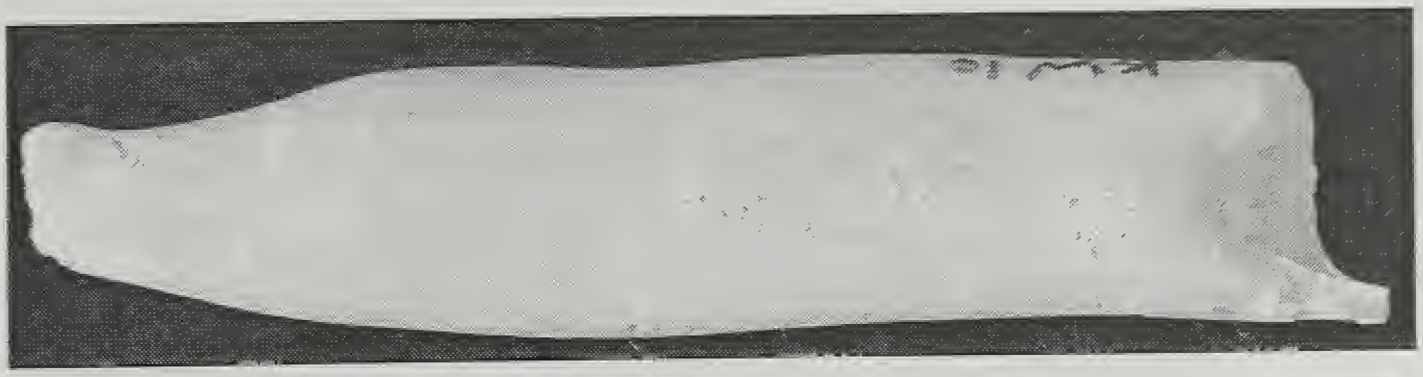

Fig. 3. Grossly distorted whole guard seen in ventral view. Note broken apex and short ventral slit extending adorally from that point. Specimen is 5.5 cm long. Author's catalogue number KW(?)10/7.

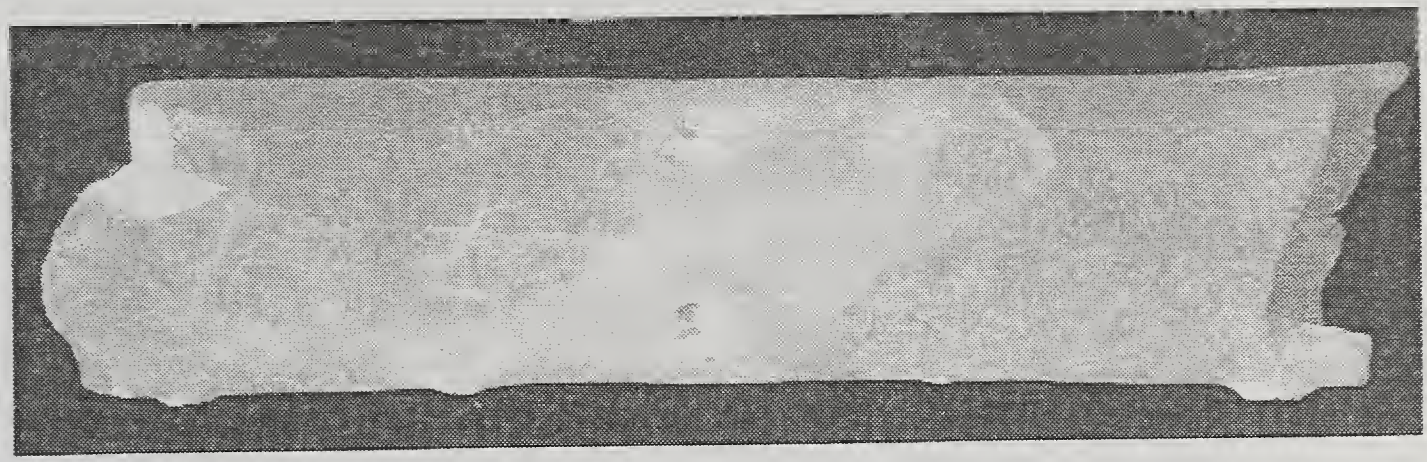

Fig. 4. Broken adoral end of a guard with a symmetrically positioned pair of closely placed, equal sized, double incisions on the dorsal surface above the ventral fissure (centre of field of view). This may be a failed predation attempt since scar tissue is present. Specimen is 5 cm long. Author's catalogue number CSE(S16)20/19.

Two specimens (author's catalogue numbers KW(?)10/8 and KW(?)10/12) exhibit equant, flat, circular scars whose peripheries are clearly incised into the guard. The scars are closely aligned and wrap around the guard and thus could not have been produced by conical teeth set in a rigid jaw, (e.g. those of a mosasaur). These are interpreted as sucker marks resulting from intra-specific interaction (Fig. 5). Belemnites had tentacles with suckers within which there was a horny rim surrounding a circle of hooks that improved their grasp on prey. The horny rim inside the suckers is inferred to have been responsible for the incised circular scars (see Lehman, 1981, p. 189). There is also often a significant degree of asymmetric swelling in-between the circular scars demonstrating that the interaction was non-fatal.

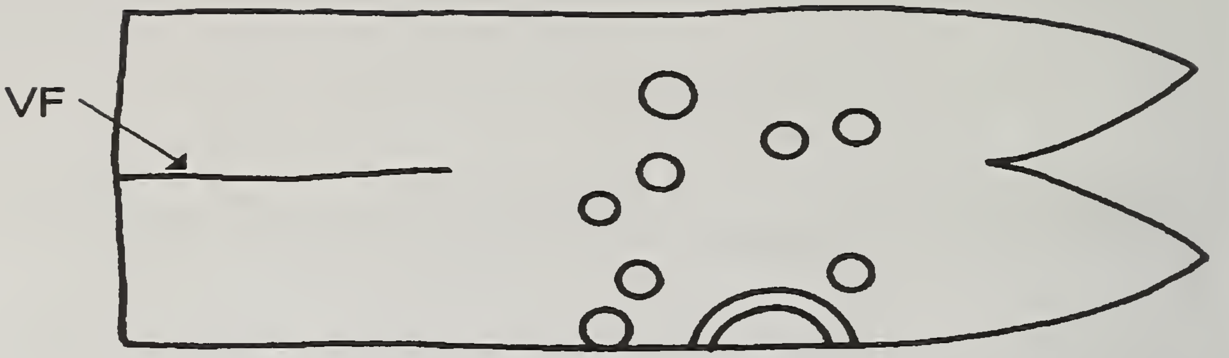

Fig. 5. Sketch of the 'unrolled' surface of a belemnite guard with position of circular and lunate scars indicated. These are interpreted as sucker marks resulting from intra-specific interaction. The ventral fissure (VF) is also arrowed. Specimen is 7.5 cm long Author's catalogue number KW(?)10/8.

In another specimen, the alveolar cavity and (by inference) its phragmocone have been crushed presumably by a predator attack. The formerly conical cavity now curves dorsally and there is a considerable amount of scar tissue surrounding the wound entry site visible inside the alveolus. The guard exterior is conspicuously asymmetric and deformed but otherwise normal.

INCORPORATION PATHOLOGIES

A very rare pathology occurs when fragments of hard tissues of other taxa are incorporated into the guard. Two specimens CSE(S5)20/3 and CSE(S13)20/13 [author's catalogue] from Caistor St Edmunds have fragments (2 mm thick and up to 10 mm across) of the large, common, benthic bivalve *Inoceramus,* embedded into their surface. The first has this located 36 mm from the guard apex at an angle of 40 degrees to the guard surface (Fig. 6). The second has the fragment incorporated into the left dorso-ventral surface 8 mm from the start of the ventral fissure.

Specimen KW(?)10/10 [author's catalogue] from Keswick has the adoral end of a belemnite alveolus 10 mm in diameter embedded into it, perpendicular to its lateral surface 10 mm from the guard apex (Fig. 7). In all specimens, the individual remained viable because the 'foreign objects' were partially overgrown by subsequent layers of the guard; moreover, in contrast to most of the other pathologies described above, no 'scar tissue' was produced.

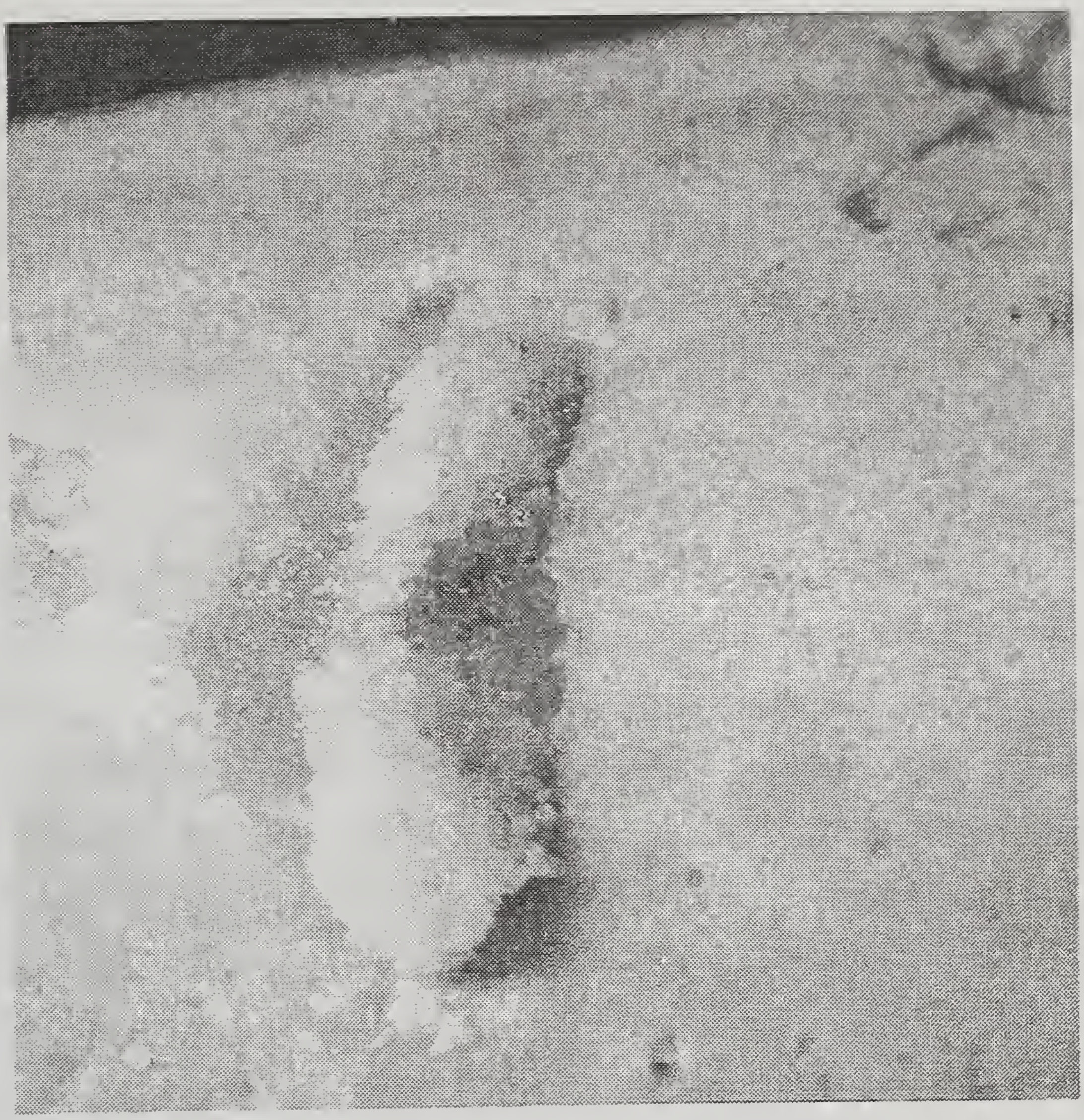

Fig. 6. *Inoceramus* shell fragment incorporated into a guard. The shell fragment is ~2 mm thick. Note that usual post-mortem biodegradation is superimposed on the surrounding area. Author's catalogue number CSE(S5)20/3.

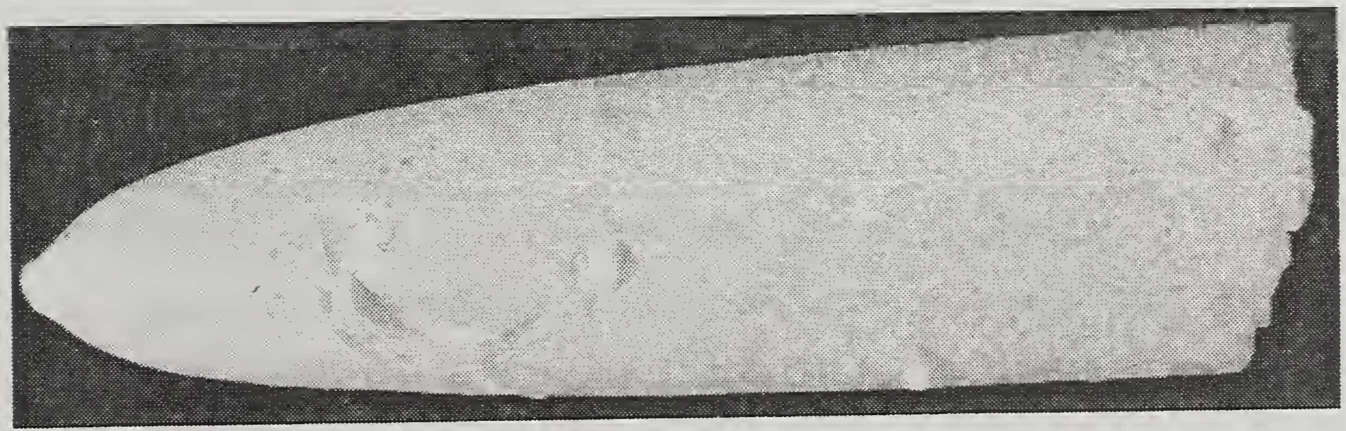

Fig. 7. Belemnite phragmocone (adoral end of guard) embedded in adapical side of another guard. Specimen is 4.5 cm long. Author's catalogue number KW(?)10/10.

BELEMNITE PREDATORS

Examples of ichthyosaurs with belemnite arm hooks in their stomach area (but not guards) demonstrate that these reptiles predated belemnites (Massare, 1988). However, no examples of ichthyosaurs are known from above the British Cenomanian. In the Upper Campanian and Maastrichtian of Norfolk the dominant predators were mosasaurs. Even partially complete mosasaur specimens are very rare; these do not show guards in the stomach area (Kuypers *et al.* 1998) and in any case it is difficult to prove that fossils are actually stomach contents (Mulder 2003, p.159).

Belemnites, being squid, were nektonic animals feeding in the near-surface waters of the Cretaceous seas. If belemnites responded to threats from predators by shoaling for protection, as some modern nekton do then, the predators probably attempted to provoke belemnites into forming defensive shoals and then targeting these shoals. Modern sharks, for example, corral squid into “bait balls” and then attack these repeatedly (Byatt *et al.* 2001). These tactics do not trap every prey item; some individuals are injured but survive and repair their injuries.

How might these attack strategies by predators produce the incorporation pathologies noted in some belemnite guards? *Inoceramus* was a sessile benthic bivalve (especially abundant in transgressive chalk facies), and lived in waters many tens, perhaps even hundreds, of metres below those typically occupied by the nektonic belemnites. This suggests that some belemnite species lived in shoals close to the seabed. In attacking, the predators presumably accidentally got mouthfuls of seafloor sediment, including *Inoceramus* shell fragments. Mastication would result in fragments of belemnites and shells being ground together and stuck into the soft tissues. Despite this some victims must have escaped and survived.

TISSUE ENVELOPE THICKNESS

It has been widely assumed, based on Naef (1922), that a tissue envelope of unknown but presumably limited thickness, enveloped and helped secrete the outermost layer of the belemnite guard. As there is no obvious sign of the foreign objects (see above) being forcibly emplaced into the pre-existing guard itself, then this tissue layer must have been sufficiently thick and robust to hold in place quite substantial ‘foreign objects’. As some of the *Inoceramus* shell fragments described above are ~2 mm thick and up to 10 mm across this suggests a minimum figure of ~2-5 mm thickness for the tissue envelope.

ACKNOWLEDGEMENTS

Thanks to Needham Chalks Ltd. for access to Caistor St. Edmund chalk pit and Frettenham Lime Company for access to the former pit at Keswick. The Head of the School of Environmental Sciences at the University of East Anglia allowed access to the scanning electron microscope, and Stephen Bennett assisted in operation of it.

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GLOSSARY

Adapical: towards the apex of (posterior) the guard, and the rear of the animal.

Adoral: towards the oral (mouth, anterior) end of the animal (front, head, tentacles, etc.).

Alveolar cavity: conical hollow in the adoral end of the guard that housed the phragmocone.

Apical line: line marking the former position of the guard apex, visible when the guard is split in the dorso-ventral plane and usually located closer to the ventral margin.

Apical generative zone: zone in immediate vicinity of the apex where clusters of spherically radiating calcite crystallites are produced, as seen along the apical line.

Congenital: having a genetic defect that expresses itself either at birth or at some later stage in the animal's life.

DVDP: the thickness of the guard in the dorso-ventral plane at the protoconch, also the location along the guard at which this measurement is made.

Phragmocone: the conical chambered shell of the belemnite animal, analogous to the shell of an ammonite and located in the alveolar cavity.

Primordial guard: early structure adherent to the outer surface of the protoconch and restricted to its apical part. This very small structure is only visible in well-preserved material in carefully prepared thin sections.

Protoconch: the initial shell of the belemnite animal located at the base of the phragmocone.

Ventral fissure: a fissure or slit in the ventral surface of the adoral end of the guard connecting its exterior with the alveolar cavity.

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TEMPORARY EXPOSURE OF NORWICH CHALK AT THE UNIVERSITY OF EAST ANGLIA CAMPUS, WEST NORWICH

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INTRODUCTION

During the last few years a number of temporary exposures of Chalk and Quaternary sediments have been created by building work on the University of East Anglia campus in west Norwich. One of the largest of these was created during excavation of the footings for the ZICER (Zuckerman Institute for Connective Environmental Research) building [NGR TG 194075] in 2001/2, where about 3 metres of Chalk were exposed, overlain by a further 2-3 metres of Quaternary sands and gravels. This short note records 1) the likely stratigraphic context of the exposure 2) the fossils recovered and 3) the contact between the Chalk and Quaternary sediments.

STRATIGRAPHY, PALAEONTOLOGY AND PALEOENVIRONMENT

A sample of very fine-grained chalk, collected ~3m below ground surface in the footings of the ZICER building was disaggregated in water and sieved to collect fossil material coarser than 1 mm. Fragments of fifteen fossil taxa were found, including bivalves (specifically oysters), brachiopods, barnacles, serpulid worms, echinoderms and bryozoa (Table 1)

Of the fossils recovered only the bryozoa (marine colonial animals) *'Membranipora' flabellata* and *'Micropora' bedensis* are of biostratigraphic value, the rest having long stratigraphic ranges. Both of these bryozoa occur throughout the Pre-Weybourne Chalks. However, knowing the subcrop of units in the Norwich Chalk of this area, it is likely the sample came from a horizon of Upper Campanian age (about 77-78 million years old) at or near the top of the Pre-Weybourne-5 unit (Wood 1988), formerly the Eaton Chalk. This stratigraphic position concurs with samples taken from

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Table 1. Fossils from the ZICER sample

Bryozoa:	*Pustulopora* spp. (2), *'Membranipora' flabellata* d'Orb., *Onychocella matrona* v. Hag., *Latereschara galeata* (v. Hag.), *'Micropora' bedensis* Brydone;
Serpulid worm:	*Glomerula gordialis* (Schlötheim, 1820);
Articulate brachiopods:	*Terebratulina* sp. (acutirostris?), *Magas* sp. indet., *Carneithyris*? sp.;
Cirripede (barnacle):	*Brachylepas* sp. (isolated valves);
Bivalves:	indeterminate juvenile oysters, probably either *Pycnodonte* or *Gryphaeostrea*;
Echinoderms:	isolated plates and ossicles:

the nearby Groundsman's Pit, in Earlham Park (Whittlesea 2002) and with outcrops exposed by construction of the Cringleford by-pass in the 1960s (Wood 1988).

The Pre-Weybourne Chalks represents a period of time when the Cretaceous sea floor was well below both the photic zone and wave base. The chalky sediment was a soft ooze, rarely if ever disturbed by current action. Some of the animals mentioned in Table 1 managed to repose on or crawl in this ooze (bivalves, echinoderms), while the others (barnacles, brachiopods and bryozoa) typically looked for hard surfaces, such as shells, to encrust. For example, the bryozoan *'Micropora' bedensis* typically encrusted whole or fragmented echinoid tests. The serpulid *Glomerula gordialis* grew by a form of self-encrustation.

The Pre-Weybourne Chalks are characterised by abundant though specialised bryozoan species. The colonies are usually small (<5 mm) mostly falling into four broad categories:

Free-living– unattached unilaminar sheet-like forms, flat or gently arched fans or obtusely conical and circular ('lunulitiform' – rather like an inverted wok!). In modern environments, lunulitid bryozoa are restricted to specialised habitats. In the Norwich Chalk it is rare to find more than two species of the genus *Lunulites s.l.*; however, the Pre-Weybourne Chalks have yielded twenty eight to date – many of them undescribed.

Capitate– ball or funnel shaped colonies with a short stalk that was anchored to the substrate by a holdfast of rhizoids, (specialised non-feeding, structural colony members). Some colonies seem to have been able to produce erect articulated and diverging colonies, (somewhat analogous to a string of beads).

Vinculariform– a general category of erect forms embracing cylindrical or narrow bilaminate (one or two rows of zooids growing back-to-back) colonies. The term is sometimes extended to apply to some more irregularly shaped erect forms; all were anchored to the substrate by rhizoids.

Frondose bilaminate– larger genera that needed a fairly substantial initial surface on which to recruit; these then grew out across or around this to provide a platform from which erect, branching, broad bilaminate fronds arose. On the sea floor the base might reach 100 mm across and the branches up to 100 mm high.

The overwhelming proportion of bryozoa from the ZICER locality were anchored basally by rhizoids directly into the substrate (capitate + vinculariform), or were free-living on the soft substrate ('lunulitiform') after first recruiting onto a tiny substrate (e.g. foraminifer test) to metamorphose from a pelagic larval stage.

The abundant free-living bryozoa were <0.25 mm thick and their extended feeding tentacles ('lophophore') would have extended little more than about 0.50 mm above the colony surface. Sedimentation rates must have been low enough to avoid smothering these free-living colonies and food availability was probably low in the absence of food-bearing currents. The tiny adult size of the bryozoa colonies reinforces this interpretation and they probably reached sexual maturity quickly (less than 28 days).

At the nearby Groundsman's Pit (Whittlesea 2002), the relative abundance of the bivalve *Pseudoptera* is instructive; it has very asymmetrical auricles: one being enormously elongated. This configuration would have ensured the animal did not recirculate water that was probably not very rich in food in the first place by maintaining a high separation between the inhalant and exhalant currents. Overall the fauna seems to have been adapted to reach maturity at a small size and reproduce where food was not abundant. Anything big probably grew only slowly or died as a juvenile (e.g. the brachiopod *Carneithyris*).

INTERFACE BETWEEN THE CHALK AND QUATERNARY SEDIMENTS

The interface between the Chalk and overlying Quaternary sands and gravels is irregular and complex, defined by about 1m of buff coloured putty chalk (Ranson 1965) arranged into discrete ridges and depressions of about 0.5 to 1metre in both height and amplitude. This complex geological boundary was described in the 1960s from the University site by Fowler & Leeder (1968) and further by Leeder (1972). The interface suggests reaction of the top of the Chalk with groundwater, to form putty chalk. The ridges and depressions could have been formed by focussed groundwater flow into fractures in the Chalk, to make small dolines (depressions). Alternatively, and perhaps more likely, the irregular interface might have resulted from ground-heave and/or differential loading (Fowler & Leeder 1968; Leeder (1972) during seasonal melting and freezing under permafrost conditions during one (or more) of the Quaternary glacial periods.

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XX(379870.1)

THE CONTENTS OF A CARDBOARD BOX (MINUTES OF THE PARAMOUDRA CLUB 1950 - 1967)

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INTRODUCTION

This article was prompted by finding the second minutes book of the Paramoudra Club in a cardboard box kept in store by the Castle Museum, combined with interest in the early years of the Society aroused by its 50th anniversary. The minutes book covers the period from 22nd January 1951 to 30th November 1968. There clearly was an earlier minutes book but it is presumed lost, together with almost all other archive material. The meetings in the book were numbered (retrospectively), possibly by C.E. Ranson or M.R. Leeder, from December 1966 onwards (p.165). [All subsequent page numbers and direct quotations derive from the minutes book]. However, the numbers refer only to those meetings that were minuted: earlier meetings from the first (missing) minutes book and the many field and committee meetings were not recorded. The numbers do not, therefore, correspond to the actual number of meetings that took place.

The minutes book contains many of the usual, and still familiar, grumbles that all societies of this type have — lack of attendance at meetings, apparent apathy, too few articles submitted for the Bulletin, late payment of subscriptions, address changes not notified and so on. On the other hand, much is of interest and entertaining.

THE BEGINNING

The Paramoudra Club had its origins at the City of Norwich School, in those days following the Higher School Certificate examinations. Before term ended in July 1950 several

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geologically-minded boys were trying to fill their time profitably. The Club was founded at 9.30 am on 13th July (Funnell 1998). There were ten founder members: J.S. Atkinson, D.C. Croghan, R. Dyer, B.M. Funnell, W.A. Gordon, I.J. Harrowven, F.A. Haverson, A.J. Martin, B.R. Richmond and R.G. Thurrell. By the end of that year a further eleven boys had joined and by the end of 1951 there were 33 members. A photograph, taken by Reg Thurrell, of the founder members and those who had joined by the end of July 1950 (with the exception of G.P. Larwood) is on the front cover of Bulletin 38A.

The Paramoudra — a large ring flint or potstone — (Peake and Hancock 1961, p.318), constitutionally the mascot of the Club, came from the Chalk pit at Caistor St. Edmund (Martin 2000) and the carrier demanded 'danger money'. It was nick-named ‘Percy’, after the geology master, Percy "Bulldog" Houghton, and was christened with hydrochloric acid! The mascot was kept outside the old School House. It is possible that when this building was demolished the paramoudra came to a sad and ignominious end and was cleared away with the rubble, no-one on site realising its significance. D.A. Lewis published a final lament in GSN Newsletter No. 23 (p. 2-3) describing the demolition as "the destruction of the breeding ground where the club evolved", with the hope that the Paramoudra would "find a caring home".

All other Club possessions were also housed at the school. Membership cards were printed and there was even, in 1958, a Club tie produced by the 'Norwich Group' (see below). The whereabouts of these Club possessions are no longer known.

CONSTITUTION

A constitution was first adopted on the 19th December 1951 (Funnell 1998) but no minutes of the meeting remain. A copy of the original constitution, with two minor amendments, was published in the first Bulletin (and reprinted in 1988 in Bulletin 38A). In general terms, members were “not bothered” about the constitution in the early years (p.102) – this was seen as “a good thing” as more time could be spent running the club. However, minor additions and amendments were added from time to time [28th December 1951, 1958 AGM (p. 113), 1961 AGM (p. 133)]. The Office of ‘Editor’ was added to the committee at the 1953 AGM, and the Office of ‘Fieldwork Secretary’ added in 1959 (p. 123).

The first major threat to the Paramoudra Club arose in January 1953, when it is minuted that the Norfolk and Norwich Naturalists' Society (NNNS) proposed to resurrect the Norwich Geological Society as a distinct section, its own geological section being long since moribund. One of the reasons for establishing the Paramoudra Club was because after World War II the NNNS provided nothing in the county for those with geological interests. It was thought that the greater financial backing of the NNNS would enable provision of better publications and bulletins, more eminent speakers and other benefits that the Paramoudra Club could not provide. Much discussion followed because of the obvious overlap: should the Paramoudra Club work hand-in-hand with the NNNS, or would there be conflict with consequent loss of membership? Should the Club concentrate on fieldwork instead? In the event, even though affiliation with the NNNS was approved on 6th July 1953 (p. 59), possibly because of pressure from the NNNS to do so, the Club membership generally believed that it should remain independent. What happened? There is no mention of affiliation in the Secretary's lengthy review (his "last fling prior to retirement") at the AGM of 23rd December 1957. It seems independence had prevailed.

A more formal and larger committee (p. 133) was introduced in 1961, designed to raise the profile of the club and add gravitas; also to bring the 'Norwich Group' (see below) into closer contact with, and simplify the running, of the club. Major changes were also associated with the changing of the name of the Club to the 'Geological Society of Norfolk'.

VENUES

Purdy's Restaurant in Tombland (Norwich) is minuted as a fairly regular venue for Committee meetings (e.g. 22nd December 1951, 3rd January 1953, 2nd April 1953). Purdy's was a firm of bakers with its HQ in Yarmouth and with branches in East Anglia (who remembers Purdy's cakes?). General Meetings were often held at the Assembly House (which was newly opened), members' homes, or the Castle Museum (all in Norwich). The 150th meeting (in 1958) was celebrated by a dinner at the Curate House, Gentleman's Walk in Norwich (p. 114). The Castle Museum proved an ideal venue and eventually became the permanent headquarters of the Club, subject to approval and agreement of the Museum authorities, with use of room and notice-board. Excellent use was made of the Museum collections, as witnessed during an informal talk given by Norman Peake — "Echinoderms and their fossil environment" (p. 184), which over 30 members attended.

LYELL

A reading from Charles Lyell's three-volume "Principles of Geology" before every meeting was item 10 in the constitution. The office of 'Reader' was specifically formalised for this function, a post copied directly from the Thomas Browne Society (school debating society). Three members, Funnell, Martin and Croghan, cycled to Great Yarmouth to buy the volumes from Farrows Bookshop for 1 guinea (Martin 2000) sometime between the Club's founding and 22nd December 1951. The first minuted reading was on the 28th December 1951, "on the necessity for all geologists to have a knowledge of fossil forms" (p. 3). It was minuted when a reading did not take place, as well as when it was read.

Occasional notes are minuted in the following years. At the 1953 AGM G.R. Tresise, presumably a member of the 'London Group' at the time (see below), resigned as Reader indicating that the volumes specifically belong to the 'Norwich Group', and he felt that it would be more appropriate if the Reader were elected from the 'Norwich Group' (p.49). Later, in 1957, "the reader should not rely on Mr. Funnell bringing his copy to meetings" (p. 109); and the reading at the April 1958 meeting "was as usual inappropriate to the evening's subject"(p. 111) — in contrast to the much earlier comment that the reading was "most apposite" (p. 3).

The last Reader was elected at the 1960 AGM. As a result of constitutional changes the following year the post was abandoned. Lyell was read for the last time by T.W. Robbins at the beginning of the AGM on 28th December 1961. The three volumes are now owned by Prof. Michael Leeder who works at the University of East Anglia

THE 'LONDON GROUP'

The early members were genuinely interested in geology and many went on to the University of London to further their geological studies: King's and University Colleges were particularly popular. At that time National Service still existed, and many students avoided it by going to the University of London and then pursuing a 'job of national importance', of which being a geologist was one. Many went into the oil industry, became geophysicists or engineering geologists, joined the Geological Survey, or became teachers or academics. A 'London Group' had formed by December 1951.

These London collegers were possibly seen as geological 'gurus' by those in Norfolk. Certainly they were able to contribute much to the Club, particularly talks: many meetings were specifically arranged in holiday time to accommodate them. With so many other distractions in London, however, the 'London Group' itself rarely (if ever) met in London during term time.

By 1957 an unhealthy "rift of non-communication had inevitably happened" between the London and Norwich groups (p. 102) — indeed, the 'London Group' was described as "the main" group. By 1967, the "monetary/subscriptive inter-relationships" had also become obscure (p. 182). Eventually the 'London Group' seems to have simply fizzled out as none of the early members were still in London.

SUBSCRIPTIONS

The annual subscription in 1951 was 2/6 [12½ p]. Even in those days late-payers were always a problem — a "pay or resign" proposal was accepted almost from the start. Later, members were rigorously excluded for non-payment. It was also proposed that permanently overseas members should be honorary, but this system became too unmanageable and was eventually dropped. Fund raising by selling specimens was suggested as a way of increasing the Club's assets — for example a dealer in Penrith was willing to pay 2/6 for a good specimen of *Echinocorys* (p. 89). Membership gradually increased, so that in 1960, ten years after the founding of the Club, there were 85 members (p. 127).

SPEAKERS

Talks in the early days of the club were often given by the members themselves and were for members only. The first recorded talk was by Brian Funnell on 28th December 1951 entitled "Recent work by members on the Norwich Crag". There followed a large variety of topics: Firman on the Lake District in Devonian times (10th April 1952); Betts on Geological excursions in Italy (25th July 1952); Thurrell on Highland geology; the Wealden Beds, the Chillesford Beds, Tas Valley geomorphology and much more.

In the General Meeting of 22nd September 1952 two speakers failed to turn up. "Finally and almost desperately" Funnell was asked to give a talk and did so for nearly an hour on borings made in the Norwich Crag (p. 22). In the vote of thanks after the talk, it was recorded that “Mr Funnell has done it again!”

Later, outside speakers were invited, providing a greater variety of topics and a higher standard. One member, however (Gordon), expressed dissatisfaction with the general tone of meetings and requested more formality (p. 18). Thurrell gave his Presidential Address for 1953 on the “History of Norfolk Geology” — an interesting comparison to that given by Wood (2000). The meeting on 21st October 1956 “started a few minutes late owing to the lack of a pointer for the speaker”, and later, “Mr Hancock used the ash pointer, which was obtained from the garden of the Assembly House, to great advantage…”(p. 92): such events would not, of course, occur today! A lengthy review of the Paramoudra Club's history was given at the 1957 AGM by B.R. Brown, the Club's secretary (p. 102).

COLLECTIONS

Members were keen to start a collection of specimens and one was in existence by February 1951 housed at the City of Norwich School and made available on loan for the use of members. Part of this early material (numbered 1-41 in the school collection) came from Lowestoft, where fishermen used erratic boulders trawled from the bed of the North Sea (some over half a ton in weight) in garden rockeries. Some of these were appropriated, or pieces chipped off them, for club use. Most was igneous in origin and many specimens were sent to the Geological Museum in London for identification. A list of the trawled Lowestoft erratics still remains in I. Harrowven's immaculately kept field note book.

There was also a large collection of Norwich Crag material, much of which originated from a survey of Crag localities. Perhaps this collection was considered to be school property, for (p. 74) in the meeting of 26th July 1954 it was suggested that “a club collection of specimens be made and curated…” to be kept at the school. Specimens collected by members were often displayed at meetings, and the first of a limited number of exhibitions were displayed by Norfolk Research Committee Junior members in April 1952 on the Norwich Crag.

A library collection was also built up, first mentioned in 1954, when Baggs stated that he was "willing to maintain a club library" (p. 74). However, it was not until three years later, following some discussion at the 1957 AGM, that the library was more formally housed in specially procured cabinets at the school in Room 3. The emphasis was very much on local geology and included many offprints. Presumably the collections of specimens, books and papers remained at the school. It would be interesting to know where they are today.

An index record of geological sites was proposed in 1952 by the Norwich Group. The original version was completed in 1954 but subsequently mislaid. It was stated as "not organised" by the secretary in 1957 (p. 102), but Funnell responded later that it was in the hands of Miss Barbara Green at the Castle Museum (p. 107) and that a new one had been compiled. An index of well records was also completed and kept at the Castle Museum. Again, the present location of these records is not known.

THE BULLETIN AND "THE GEOLOGY OF NORFOLK"

On 26th March 1953 Baggs, who was then Treasurer, suggested "some form of club news bulletin be prepared" (p. 55). Baggs could apparently offer low duplication costs. This was approved and Baggs was elected editor (in his absence). Baggs sent out a letter to members on 13th April 1953 (copied in Bulletin 38A) explaining the aims of the new bulletin and requesting contributions. It was intended to include abstracts from geological journals and papers, bibliographies, research reports, exposure records and more.

The Bulletin was first published in September 1953 with contributions from Baggs, Martin and Larwood and cost "over £1 to produce" (p. 66). The new office of Editor was created at the AGM of 26th December 1953 and Baggs was elected to the post. The 'Norwich Group' also decided to produce it's own newsletter (p. 114); only one issue was printed and there was not enough material for a second.

It was decided to produce a special publication to celebrate the 10th anniversary of the club, to be published in 1960. It took two years to plan, being discussed as early as April 1958 (p.112): a sub-committee was formed (p.114) to investigate production — editing, printing method and finance. Authors were invited to contribute and members were invited to pay in advance to help with the costs: other prospective buyers were also sought (p. 120). The edition was first referred to as "The Geology of Norfolk" at the AGM in December 1960 (p.127). It was finally published in 1961 as Part 6 of Volume 19 of the Transactions of the Norfolk and Norwich Naturalists' Society. Edited by G.P. Larwood and B.M. Funnell, it contained papers by R.G. Thurrell (Sub-Cretaceous Rocks of Norfolk), G.P. Larwood (The

Lower Cretaceous Deposits of Norfolk), N.B. Peake and J.M. Hancock (The Upper Cretaceous of Norfolk), B.M. Funnell (The Palaeogene and Early Pleistocene of Norfolk) and R.G. West (The Glacial and Interglacial Deposits of Norfolk). 1250 copies were printed, of which 600 were for the NNNS, at a cost of £402/5/-. A grant of £150 had been obtained from the Royal Society (p. 132), £120 came from the NNNS, and the remainder was loaned by A. Baggs. Subsequent profits went to the club, and by December 1965 less than 75 copies remained unsold. Initially it cost 7/6d + 6d postage to buy. "The Geology of Norfolk" was reprinted unchanged in 1970, but with additional references and some other addenda, and cost 15/- (75p).

The mid-1960s saw further ambitious aims — the printing of a simple guide to the Geology of Norfolk for schools; descriptions of well-known important exposures to be written up for the Bulletin; and a geological guide to East Anglia, in the form of an excursion guide, to be produced for the British Association in 1965. A 'Geology of Suffolk' was also considered (p. 148).

A 'new improved look' to the Bulletin, as part of a general move to upgrade the status of the club and improve it's scientific standing, was discussed from March 1967 (p. 172). Improvements were to include the content, particularly with a view to stimulating original research, a change to better production methods, and seeking a market for wider sales. The aim was to produce a recognised scientific publication of one issue per year (p. 180). One of the proposed names was "The Paramoudra - a Journal of East Anglian Geology" and in fact was carried unanimously (p. 182) - although history demonstrates that the name-change never actually took place.

FIELD TRIPS

Field meetings took place from the earliest days, often as valuable post-exam field-based projects (p. 101), and to a great extent were the *raison d'etre* for the club. Furthermore, the members recognised the need to "see rocks" and generate consistent themes of innovative and original work. Work was written up in the club field books including records of wells and temporary exposures. In the days before mass car ownership, localities near to Norwich were often visited on bicycle.

Field meetings were minuted: the first being that of 3rd January 1952 "under somewhat frigid conditions" by car to Spixworth Chalk Quarries, then to Frettenham gravel pits. They lunched "under the kind auspices of British Railways" in Norwich and prepared a 'Paramoudra Club' nameplate "on the Presidential expenditure of 1d". They then drove to Whitlingham Crag pit and, "following a slight altercation between the President's car and an esteemed member of the club", went on to Arminghall Quarry, where "a search was made for a portable paramoudra suitable for presentation to Queen Mary College Geological Society" (p. 7).

Projects included:

1. An investigation of alluvial deposits of the River Yare in the Newmarket-Ipswich-Eaton Roads area of Norwich – 40 borings to a maximum depth of 18ft were made, mapped and sections drawn; Funnell was also given access to the city engineer's boring samples. Houghton arranged this for Funnell as it was seen that he needed something substantial to work on for his Cambridge scholarship examinations in the 3rd year of the sixth form. An abstract by Funnell was published in Bulletin 2 (1954). This was the first piece of 'proper' research done by a Paramoudra Club member (p. 23).

2. A survey of Norwich Crag sites; Harrowven did some heavy mineral analyses (p. 16) and still possesses the meticulous results of these investigations, with details of the sections, maps and faunal lists. The final account was compiled by Hunter, Funnell and Martin.

Sections were cleared by members for the 1961 British Association meeting (p. 128), and meetings in 1963 (p.140) led to the publication of first issue of a new 'Norwich Group Fieldwork Bulletin' by Hart. The first of these, produced in December 1963 by C.N. Hart, was a report of pebble orientation in the Norwich Brickearth at Lodge Lane and Mile Cross Lane (Norwich), and in the Lower Till at Mundesley. It would appear that few further 'Fieldwork Bulletins', if any, were published.

Localities visited on trips were very similar to those visited today. Much use was made of public transport, but sometimes coaches were also hired. By the late 1960s there was more use of private cars: not only were they more convenient but they also saved the Club money. Certainly as much as possible was packed into the day. For example: a bus trip to Weybourne on 30th August 1952 (where the previous minutes were signed); a trip by train to Southwold, Easton Bavents and Covehithe on 28th March 1953; a trip by car to Chillesford Church on 9th August 1953, with lunch at the Oyster Inn, and then on to Butley for Red Crag and Bawdsey Cliff, with tea at the Tudor Café (Saxmundham) and again at the President's (Thurrell) house; a trip to Ipswich Museum with H.E.P. Spencer as guide, and on to Sutton for some Coralline Crag and Bawdsey (during which the bus was in collision with a pheasant — the return journey made "without noteworthy incident")(p.126).

C.E. Ranson was a great exponent of local work (p. 170-171) and was President for 1967 (the Lord Bishop of Norwich had in fact been elected (p. 168) but had declined the post) giving a talk on the subject on 25th March 1967. A field meeting the following day was at Arminghall and a committee meeting took place during the lunch break.

An excursion to Caister-by-Yarmouth on 11th August 1955, minuted by A.J. Martin reads: "a ridge of high pressure covering the British Isles showing no sign of breaking up, a party assembled and proceeded to Caister-on-Sea — transport provided by the Eastern Counties Omnibus Co. Ltd. There, having made their way over and around forms prostrate on the substrate, members examined the cliffs (Pleistocene). Meanwhile, the leader, having seen it all before, sank to the sand (Recent) and surveyed the topography in a general easterly direction. Tea was taken at 4.30pm and a bus at 5.30pm. Three members were present." (p. 82).

The minutes also reveal other insights, for example:

"To celebrate the 100th meeting of the group, in 1956, a camp was established at Bramerton; on the stroke of midnight [? should this really be 'mid-day'] the section was attacked and a limited fauna collected, the group then rested till opening time, when they made their way to the Woods Inn." [written by B.R. Brown] (p. 94).

"Mr. Treasurer [F.J. Wright] provided some light entertainment for the party by a demonstration of hare stalking — his efforts, however, being unsuccessful." (p. 171)

THE CHANGE OF NAME

A change of Club name was first proposed as long ago as the AGM on 22nd December 1952 by Daly. Seconded by Larwood, he sought to change the name to "Geological Society of East Anglia (Paramoudra Club)" on the grounds that the existing name was not self-explanatory and a new name would attract greater membership. Much discussion ensued, with the main opposition by Harrowven. Eventually it was decided, by 10 votes to 3, to change the name, but a suitable name could not be agreed. 'East Anglian Geological Society' was the most favoured, but with a vote of 6 for and 6 against, did not carry the proposal.

There was a further proposal in December 1960 (p. 128) that "Norfolk Geological Society" be incorporated into the name: this was amended to be simply an explanatory note and carried by 19 votes to 3. Four years later, there was again a decision by the Committee (p. 147) to change to the "Geological Society of East Anglia (Paramoudra Club)", but at the AGM no votes were cast in favour (p.152). Yet again, during a Committee meeting on 26th March 1967 during a lunch break on a field trip, there was a decision to change the name to "Norfolk Geological Society", particularly in view of the proposed expansion of the Bulletin (same meeting p. 172).

Finally, the Paramoudra Club voted to become the Geological Society of Norfolk by 21 votes to 1 at the AGM on the 28th December 1967. The Paramoudra Club had 84 members at the time (p. 182). However, even then there was controversy: an EGM on 30th November 1968 records that the name change of both the Club and its publication had met with disfavour from those present and from the majority of those sending written comments. Further, it is doubtful if the resolution (of the proposal to change the name) was legally enacted as the proposer was not by the terms of the constitution a member of the Club at the time it was passed. The draft constitution for the Geological Society of Norfolk (drawn up by committee on 30th September 1968) was therefore rejected and a postal referendum initiated.

The result of the referendum — 35 replies received out of a possible 79 — indicated no clear preference between 'Geological Society of Norfolk' and 'Geological Society of East

Anglia', but a clear preference for one or other of the two titles. In the interests of continuity, the committee recommended the retention of 'Geological Society of Norfolk'. A further EGM was held on 2nd October 1969 at which this, and the draft constitution drawn up in June of that year, were formally adopted. This was clearly an unhappy and frustrating time for the Club.

ENDPIECE

During the past 50 years times have changed sociologically for clubs and societies. In the 1950s clubs of this type were very popular as leisure pursuits. Their popularity has, however, been on the wane for many years as other leisure activities have emerged. Whereas before, participation was the key to a thriving success, it is clear that now members join for different reasons —the highly regarded Bulletin, for one. Bear in mind also that the Paramoudra Club was founded by young people, who, by and large, had geology as a goal for a career in later life. That focus has changed amongst school leavers and new university intake, and indeed the age structure of membership has changed accordingly.

The Geological Society of Norfolk, as with many other comparable clubs and societies, faces exacting challenges if it is to survive in the future. The last word on the Society should go to Brian Funnell (1998) “let us hope it will retain its enthusiasm for geology, and everyone who enjoys it, for a long time to come”.

ACKNOWLEDGEMENTS

The author is indebted to John Martin, Tony Baggs and Ivor Harrowven, three members from 1950, for their very kind hospitality, for allowing me to pick their brains for their recollections of the Paramoudra Club, and for their invaluable comments and suggestions. This article would not have been possible without them. The author would be pleased to hear of any further recollections from Paramoudra Club members, and asks that they contact him.

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The Geological Society of Norfolk exists to promote the study and understanding of geology in East Anglia, and holds meetings throughout the year. For further details consult our Web Site (http://www.norfolkgeology.co.uk) or write to The Secretary, Geological Society of Norfolk, 32, Lenthall Close, Norwich, NR7 0UU.

The illustration on the front cover is figure 4 from the first article by Whittlesea in this issue of the Bulletin. It shows differences in the growth lines of the Norfolk Chalk belemnites *Belemnitella* and *Gonioteuthis*.

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